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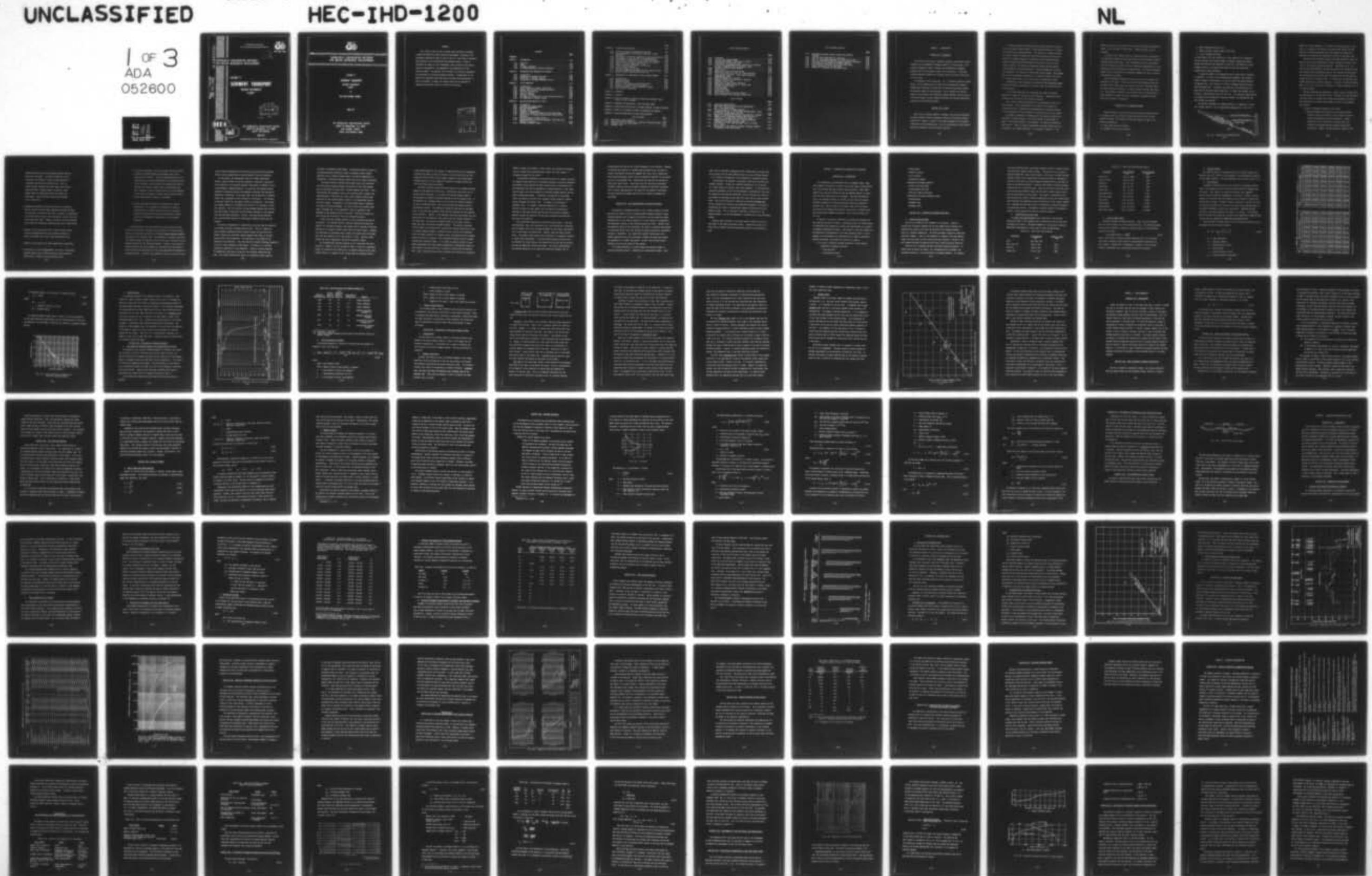

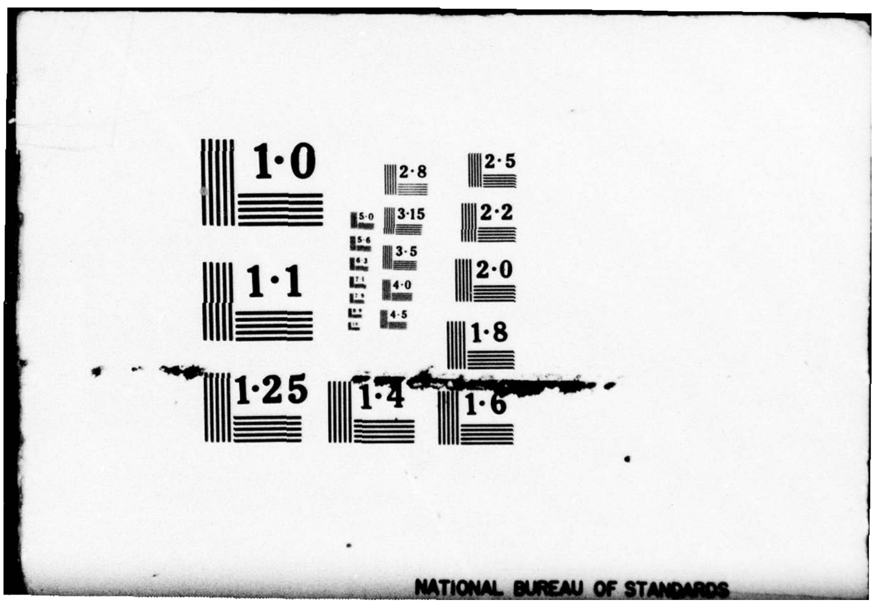
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NATIONAL BUREAU OF STANDARDS

A United States Contribution
to the International Hydrological Decade

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12

HYDROLOGIC ENGINEERING METHODS FOR WATER RESOURCES DEVELOPMENT

VOLUME 12

SEDIMENT TRANSPORT

WITHOUT APPENDICES 6 AND 7

HEC

THE HYDROLOGIC ENGINEERING CENTER
CORPS OF ENGINEERS, U.S. ARMY
DAVIS, CALIFORNIA

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HYDROLOGIC ENGINEERING METHODS FOR WATER RESOURCES DEVELOPMENT

VOLUME 12

SEDIMENT TRANSPORT

WITHOUT APPENDICES
6 AND 7

by

WILLIAM ANTHONY THOMAS

JUNE 1977

THE HYDROLOGIC ENGINEERING CENTER
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FOREWORD

This volume is part of the 12-volume report entitled "Hydrologic Engineering Methods for Water Resources Development," prepared by The Hydrologic Engineering Center as part of the U.S. Army Corps of Engineers' participation in the International Hydrological Decade. Volume 12 addresses the topics of river morphology, data collection and analysis, reservoir sedimentation, and aggradation and degradation in free flowing streams. The emphasis of the volume is on practical approaches and techniques for analyzing sediment problems. Although many of the methods and procedures described herein have been used successfully in Corps of Engineers' studies, the volume should not be construed to represent the official policy or criteria of the Corps.

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CHAPTER 1. INTRODUCTION

Section 1.01. Objective

The title of this volume, "Sediment Transport," was chosen to focus attention on the movement of sediment material in flowing water. This involves processes of scour, transport and deposition of inorganic material both in free flowing streams and in reservoirs. While some sediment transport formulas are included, they do not form a major part of this volume.

The purposes of this volume are: (1) to identify potential problem areas; (2) to identify which of these can be analyzed with existing mathematical techniques and which must be studied using either movable bed hydraulic models or the prototype; (3) to identify the type and amount of data required for analyzing sediment problems, and (4) to give sufficient guidance so that competent engineers may develop satisfactory solutions to the sediment problems.

Section 1.02. Scope

Basic to all sediment studies is sediment yield from the watershed. The paper entitled "Corps of Engineers Methods for Predicting Sediment Yield" by Mr. Robert H. Livesey is included as Appendix III to provide information in this problem area. Also, the calculation of land surface erosion is presented, but only briefly described.

The basic concept of calculating water surface profiles in natural rivers is extended beyond Volume 6, "Water Surface Profiles," to include the river bed as a movable boundary. The analysis of sediment problems by digital computer simulation is useful for calculating the volume and location of sediment deposits in reservoirs and for predicting aggradation or degradation trends downstream from dams as well as in free flowing streams. The Hydrologic Engineering Center computer program which performs the simulation analysis, "Scour and Deposition in Rivers and Reservoirs," is included in Appendix VII of this volume. This program can be used to evaluate the behavior of a stream bed during the passing of a single flood event or for a long period of hydrographic record.

Techniques are also presented in Appendix VII for calculating growth of the armor layer, destruction of the armor layer and hydraulic sorting of grain sizes.

A very useful technique for calculating the volume of sediment deposits in reservoirs is based on trap efficiency. Application of the technique does not require the electronic computer.

Since present analytical techniques do not completely define sediment problems, a good understanding of the behavior of natural and controlled streams is essential for interpreting any calculated results. A brief discussion of river morphology is included to aid in this regard.

In summary, attention is directed toward the analysis of water born sediments in defined channels. The regime concept is not treated in detail. Wind blown sediment is not included. The impact of sediment on water quality - that is, quality constituents that might adhere to and be transported with sediment particles - is discussed in Volume 11. The

growth and decay of bed forms and two and three dimensional hydrodynamic models are not included in this volume. Coastal processes are not addressed.

In general, the formulas which are included have been incorporated into analytical methods and have been applied to a wide range of problems throughout the United States. Their performance has been satisfactory when the methods were applied with the appropriate understanding of river morphology and the limitations of present theory. Even the most advanced methods require a great deal of engineering judgment to insure a correct interpretation of results.

Not all analytical techniques in use in the Corps of Engineers are included in this volume. This does not imply that techniques which are included are the "best" ones, nor does it imply that techniques which were not included are inferior. It simply reflects the fact that there are a large number of methods in use, there is only a limited amount of space available to present them, and the methods presented have been found to be generally satisfactory.

Section 1.03. A Summary Statement

Nature maintains a very delicate balance between the water flowing in a natural river, the sediment load moving with the water and the stream's boundary. Any activity of man which changes any one of the following parameters :

- water yield from the watershed
- sediment yield from the watershed

- water discharge duration curve
- depth, velocity, slope or width of the flow
- size of sediment particles,

or which tends to fix the location of a river channel on its floodplain and thus constrain the natural tendency to meander, upsets the natural balance and initiates the formation of a new one. The objective of most sediment studies is to evaluate the impact on the flow system from changing any of these parameters.

A classical example is the deposition which results when a reservoir is impounded. In terms of the aforementioned parameters, the reservoir causes a change in the hydraulics of flow by forcing the energy gradient to approach zero. This results in a loss of transport capacity with the resulting deposition. The smaller the particles, the farther they will move into the reservoir before depositing. At times fine sediment in the inflow to a deep reservoir does not fully mix. The resultant stratification is conducive to the formation of density currents, and some material may pass through the reservoir.

The obvious consequence of sediment deposits is a depletion in reservoir storage capacity. This is represented schematically in fig. 1.01,

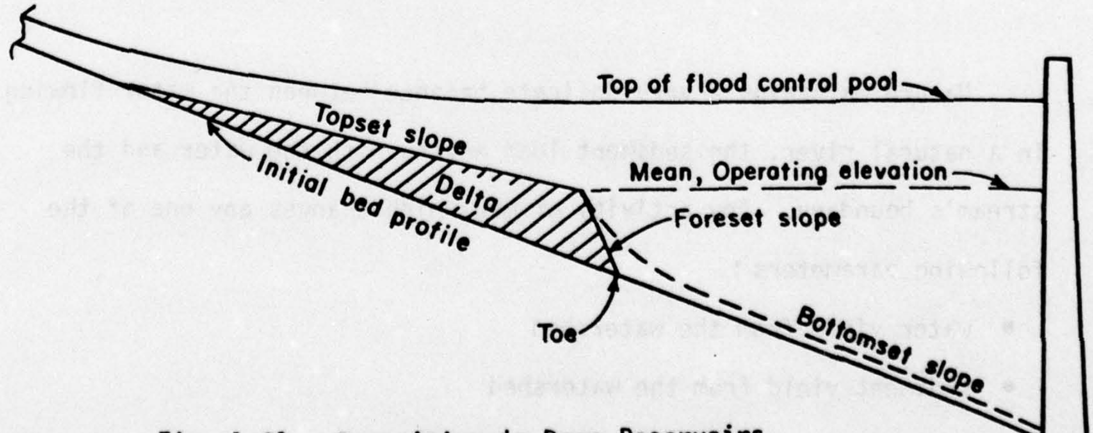

Fig. 1.01. Deposition in Deep Reservoirs

Deposition in Deep Reservoirs. The volume of sediment material in the delta is a function of the project life among other things, and that delta will continue to develop, with time, beyond the project life. Eventually a new channel and floodplain will exist in the delta area.

Identifying this deposition pattern with deep reservoirs raises the question "what is the significance of deep as opposed to shallow reservoirs on the sediment deposition pattern?". Referring to fig. 1.01, consider what would happen if the dam were moved in the direction of the delta deposits and the operating rule for the reservoir did not change. The configuration of the delta would not change until the dam actually reached the toe of the delta itself. At some point, the reservoir could become classified as a shallow reservoir. Therefore, the delta formation shown in fig. 1.01 could be as applicable to a shallow reservoir as it is to a deep reservoir.

The mean operating pool elevation is a major factor in establishing the configuration of the reservoir delta. Therefore, to shift the dam to a location along the present topset slope would completely change the mean operating pool elevation and thereby the shape of the reservoir delta itself.

A number of associated problems can be listed:

- Deposits forming the delta may raise the water surface elevation during flood flows in such a manner to require special consideration for land acquisition. In deep reservoirs, this is usually not a problem within the reservoir area because project purposes dictate land acquisition. However, the delta tends to develop in the

upstream direction and cause problems upstream from the reservoir area proper. In shallow reservoirs, on the other hand, the increase in water surface elevation is a problem even within the reservoir area. That is, floods of equal frequency may have higher water surface elevations after a project begins to develop a delta deposit than was experienced before the project was constructed. Land acquisition studies must evaluate such a possibility.

- Aggradation problems are often more severe on tributaries than on the main stem and these locations are often desirable for developing recreational facilities. Analysis is complicated by the lack of basic data on the tributaries - usually less than on the main stem itself. However, the useful life of recreation sites should be evaluated by predicting the rate of delta growth.

- Because of the high moisture level, reservoir deltas often attract phreatophytes which in many areas contribute to water use problems due to their high transpiration rate.

- Reservoir delta deposits are often aesthetically undesirable.

- Particularly in shallow impoundments, the results of reservoir sediment deposits may increase the water surface elevation sufficiently to impact on the ground water table.

- In existing reservoirs, the United States Fish and Wildlife Service is utilizing delta and backswamp areas in the prop gation of wildlife. Since the characteristics of this delta area are so closely controlled by the operating policy of the reservoir, any reallocation of storage would need to consider the impact on present delta and backswamp areas. This represents a type of problem that may be more important in the future if changing priorities among project purposes demand reallocation of storage in reservoirs.

- Looking downstream from the dam, degradation is usually predominant. It is necessary to evaluate the impact of degradation on a tailwater rating curve at the structure. Problems downstream from the dam are sufficiently complex that they are presented in some detail in the following paragraphs.

Downstream from the dam the hydraulics of flow (velocity, slope, depth and width) remain unchanged from conditions in the natural state. However, the reservoir has acted as a sink and trapped sediment material, especially the bed material load. This reduction in sediment yield from the watershed causes the energy in the flow to be out of balance with the boundary material for the downstream channel. Because of the amount of available energy, the water attempts to re-establish the former equilibrium sediment load from material in the stream bed, and this results in a degradation trend. Initially, the degradation trend may persist for only

a short distance downstream from the dam since the equilibrium sediment load is soon re-established by removing material from the stream bed.

As time passes, the degradation trend will migrate downstream; however, several factors are working together to establish a new equilibrium condition in this movable-boundary flow system, in addition to this re-entrainment of sediment material. On one hand, the potential energy gradient is decreasing because the degradation migrates from upstream to downstream in direction. On the other hand, the bed material is becoming coarser and, consequently, more resistant to being moved. This tendency in the main channel has the opposite effect on tributaries. Their potential energy gradient is increasing which results in an increase in transport capacity. This will usually increase sediment passing into the main stem which tends to stabilize the main channel resulting in less degradation than one might anticipate. Finally, a new equilibrium condition will be established between the flowing water-sediment mixture and the boundary.

The extent of degradation is complicated by the fact that the reservoir also changes the water discharge duration curve. This will impact for great distances downstream from the project because the existing river channel reflects the historical phasing between flood flows on the main stem and those from tributaries. That phasing will be changed by the operation of the reservoir. Also, the flow will probably encourage vegetation to grow at lower elevations in the channel. The result is a condition conducive to deposition in the vegetation. Actually, numerous examples of aggradation trends may be cited for river channels downstream from dams. The primary problem which results is inadequate channel capacity

resulting in inadequate levee height. Consideration should be given to performing detailed simulation studies to determine future channel capacities and to identify problem areas of excessive aggradation or degradation. Particular attention should focus on all major tributaries.

An equally classical problem results when levees are constructed for flood control purposes because the position of the river channel must be stabilized to insure that it remains between the levees. River flow entering the backwater curve to its receiving water, whether that receiving water is the ocean or a lake, loses transport capacity and deposition of the coarser material results in an aggradation trend in the river channel. Consequently, the levee height becomes inadequate to contain the design discharge. The rate at which this process takes place, although slow, is not measured in terms of geological time. Depending on the sediment yield in the basin, significant changes can occur during the 50-100 year life of an engineering project.

A third classical sediment problem is that of maintaining depth of navigation. This problem requires a detailed understanding about the behavior of the movable boundary flow system since it requires fixing the location of a navigation channel within the main channel itself. However, the techniques for performing these studies can proceed under the assumption that the location of the river channel is fixed. Hydraulic model studies can then be employed to design the navigation channel.

The aforementioned sediment problems are all associated with man's activities. However, left to its natural state, a river will continually change its position on the flood plain, its meander pattern and the cross section shape as it responds to the flowing water and sediment mixture.

A good understanding of this process is required before one can adequately interpret the impact of man's activities, for man's activities not only change the rate at which a river channel responds to the flowing water-sediment mixture, but also change the location of sediment sources and sinks from those naturally existing.

The level of detail required for the analysis of any sediment problem depends on the objective of the study. Considering a dam site as an important natural resource, it is essential to provide enough volume in the reservoir to contain anticipated deposits during the project life. If the objective of a sediment study is just to know the volume of deposits for use in screening studies, then trap efficiency techniques provide a satisfactory solution. The important information that must be available, then, is the water and sediment yields from the watershed and the capacity of the reservoir. However, if the sediment study must also address the land acquisition for the reservoir, then knowing only the volume of deposits is not sufficient. The location of deposits must also be known, and the study must take into account sediment movement. The approach presented in this volume is to analyze such a problem with digital simulation of flow in a mobile boundary channel. Sorting of grain sizes must be considered since the coarser material will deposit first, and armoring must be accommodated since scour is involved. This simulation technique actually becomes a movable-bed analytical model. It is useful to predict erosion or scour trends downstream from a dam, general aggradation or degradation trends in river channels, and the ability of a stream to transport the bed material load. Such a technique does not have to define the location of a navigation

channel in order to be useful; in fact, there is no analytical technique that is suitable for calculating where, within the river channel, a navigation channel will be stable.

The simulation technique is structured entirely for computer solution. The amount of data that has to be analyzed includes all the basic geometric and hydraulic data required for water surface profile calculations plus data describing the size and gradation of sediment material in the stream bed and banks, the size and amount of inflowing sediment material and the water discharge hydrograph. In addition, long periods of hydrograph record are generally utilized since sediment studies attempt to predict trends throughout the project life. The number of calculations is extremely large. For example, predicting deposition in a shallow reservoir having a 50 year design life can require a calculation of some 600 to 1000 water surface profiles plus the routing of sediment material through the reservoir for the water discharge associated with each one of the profiles.

Data acquisition programs have evolved to satisfy needs. With only few exceptions, data, when collected at all, are collected for estimating annual sediment yield where suspended sediment is the primary contributor. This is definitely one problem area. However, there are other problem areas. For example, data should also be collected in a systematic program to study channel morphology. This would require measuring the bed load to determine the amount moving, the gradation of the load and the sorting that goes on among the various grain sizes. The link to understanding the feedback mechanism in the water-bed interaction probably lies in

understanding bed load and the lateral movement of river channels. Attempts to simulate the behavior of a movable bed analytically will continue to require considerable qualitative judgment until this link is understood. Even present techniques require data on gradation of material in the stream bed and in the sediment load. Sampling the bed load will be required to obtain this type of data. These data should be collected by personnel intimately familiar with both sediment movement and analytical techniques until a better understanding of the nature of the problem is developed. All data acquisition programs should utilize "standard" equipment and techniques.

Section 1.04. The Interpretation of Analytical Results

The analysis of sediment problems is not a simple extension of fixed bed hydraulic theory so that it becomes movable boundary hydraulic theory. Sediment problems vary in degree of difficulty from the relatively simple determination of the volume of deposits in a deep reservoir to aggradation and degradation studies in free flowing streams and rivers. Whereas fixed bed hydraulic theory is well developed, the analysis of movable bed problems is complicated by the fact that the body of theory available for performing analyses is incomplete. The interactions between flowing water and a movable boundary are not well understood, although the water and boundary are components of a closed loop system. At best, the available theory addresses only bits and pieces of that system.

It is often uncertain as to how to apply the available theory to obtain satisfactory results. Guidelines are conspicuously absent. Case

after case is presented to demonstrate the inconsistency of results that one can obtain for the same problem analysis by using different methods -- all of which are recognized in the literature as acceptable methods.

Nevertheless, the engineer is constantly faced with the analysis of sediment problems. Perhaps the following suggestions will be helpful. It is good practice to follow a three step procedure: (1) calibrate the analytical technique, (2) verify the procedure by performing a "base test" for comparison with observed conditions, and (3) interpret the impact of any changes by reference to that base test rather than by absolute magnitudes. Due to the difficulty of obtaining consistent **prototype data** and the uncertainties involved, good engineering judgment is required in determining the source of discrepancies between calculated results and measured values. This is especially important in simulation of the movable boundary, but the same approach is valuable even in trap efficiency studies.

Another useful technique is to select several formulas for use in each phase of the study and compare results. Sensitivity studies will often help to identify the most appropriate formula for the problem at hand.

CHAPTER 2. TERMINOLOGY AND PROPERTIES OF SEDIMENT

Section 2.01. Introduction

The terminology in sedimentation work is somewhat unique. Some terms appear to be general in nature, such as bed load, or bed material load, and yet they have been defined rather precisely. Other terms appear to be very well defined and yet are somewhat general in nature; particle size classification is an example. The fact that particle size is an important variable is obvious, and yet there are several different standards for classifying sediment material according to particle size. Many of these use the words "sand, silt, and clay," but particle size diameter for material called sand is different from one classification standard to another. This is also true for silt and clay.

In general, the physical properties of sediment are important to both quantity and quality studies. Consistency within the United States in determining these properties required the establishment of a special interagency sedimentation project. The project is under the auspices of the Committee on Sedimentation of the Water Resources Council, and is engaged in the development and standardization of sampling equipment, sampling techniques, and methods for analysis of samples.

It is useful to organize sediment properties in three groups:

Properties of sediment particles

- Size and shape
- Classification scale

- Shape factor
- Specific gravity
- Fall velocity
- Gradation of sample

Properties of sediment deposits

- Initial unit dry weight
- Consolidation with time
- Unit dry weight of mixtures

Properties of the water-sediment mixture

- Concentration
- Sediment load
- Sediment yield

Section 2.02. Properties of Sediment Particles

a. Particle Size and Shape

Particle size refers to the "diameter" of a particle. There are several ways to measure diameter but the most common are by sieving or by measuring the velocity with which the particle falls through quiescent water at a standard temperature. The latter procedure produces an equivalent spherical diameter -- that is, the diameter of a sphere of the same specific weight that would have the fall velocity that was observed. Sieving is the most common technique for measuring the sizes of sand and gravel particles.

Particle size is probably the most significant physical property. It affects the resistance to erosion, the transportability of sediment, and subsequent behavior in the consolidation of sediment deposits. For example,

very small particle sizes, up to about 0.004 mm, exhibit a strong influence from electrical charges on their surface. They are said to be cohesive. Material having this range of grain sizes is called clay, and when sediment problems involve clay a special body of analytical theory is employed to account for the impact of electro-chemical characteristics of the water on those of the sediment material. Particle sizes between 0.004 mm and about 0.0625 mm are in a transition range. They are too large to feel much influence from the electromotive forces and too small to mobilize much inertia against being moved by flowing water. This range is classified as silt. When particle size exceeds 0.0625 mm electromotive forces are insignificant. These particles are noncohesive and are classified as sand, gravel, cobbles, etc. Knowledge of mechanical forces is sufficient to analyze the behavior of noncohesive sediment. Consequently, transport theory for noncohesive material is more advanced than that for cohesive material.

b. Classification by Grain Size

The grain size classification scale established by the American Geophysical Union is the standard used to relate grain size to size class throughout this volume. The median diameter of a size class is that for which 50% of the material in that class is finer and 50% coarser.

Table 2.01. Grain Size Classification

Size Class	Grain Diameter (mm)	Median Diameter (mm)
Clay	less than .004	-
Very fine silt	.004 to .008	.0057
Fine silt	.008 to .016	.0113
Medium silt	.016 to .032	.0226

Table 2.01. Grain Size Classification (cont.)

Size Class	Grain Diameter (mm)	Median Diameter (mm)
Coarse silt	.032 to .0625	.0447
Very fine sand	.0625 to .125	.0884
Fine sand	.125 to .250	.1768
Medium sand	.250 to .50	.3536
Coarse sand	.50 to 1.00	.7071
Very coarse sand	1.00 to 2.00	1.4142
Very fine gravel	2.00 to 4.00	2.8284
Fine gravel	4.00 to 8.00	5.6569
Medium gravel	8.00 to 16.00	11.3137
Coarse gravel	16.00 to 32.00	22.6274
Very coarse gravel	32.00 to 64.00	45.2548

c. Particle Shape Factor

Sediment particles are seldom spherical. Clays are very elongated and, to a lesser extent, so are the larger particles. The following expression has been proposed as a measure of particle shape by using dimensions normal to each other:

$$\text{grain shape factor} = c/\sqrt{a \cdot b} \qquad (2\text{-}01)$$

where a and b refer to the two smallest dimensions and c to the largest. The primary influence of grain shape in the noncohesive particles is on fall velocity. Whereas this is recognized in concept, it has not been formally incorporated into a satisfactory analytical expression.

d. Specific Gravity

The specific gravity of sediment particles is another property that impacts on the fall velocity, and consequently, the hydrodynamic properties of the sediment particle. The value commonly used for quartz sand is 2.65.

e. Fall Velocity

A property of sediment which is very important in transport calculations is the velocity at which a single particle would fall through quiescent water. This velocity is related to the grain size, specific gravity, particle shape and temperature of the water. Usually, the fall velocity is calculated from the sediment particle diameter as though that particle were a sphere. Although it seems, intuitively, that the fall velocity should be corrected for the shape of the particle, presently there is not enough information to make such a correction. Therefore the fall velocity is calculated assuming the particle is a sphere. The following table 2.02 shows fall velocities for quartz sand (which has a specific gravity of 2.65) as a function of temperature and particle size.

Fall velocities for other sizes or for other specific gravities may be calculated with the following equation:

$$w^2 = \frac{4}{3} \cdot \frac{g \cdot d}{C_D} \left(\frac{\gamma_s - \gamma}{\gamma} \right) \tag{2-02}$$

C_D = drag coefficient

d = particle diameter

g = acceleration of gravity

w = fall velocity

γ = specific weight of fluid

γ_s = specific weight of the sphere

Table 2.02. Sand Grain Settling Velocity Versus Temperature, SP.G. 2.65, Shape Factor 0.9 [1]

TEMP °F	SETTLING VELOCITY IN FT/SEC							
	VFS	FS	MS	CS	VCS	VFG	FG	MG
35	.013	.045	.130	.305	.590	1.00	1.41	1.95
36	.013	.045	.131	.307	.592	1.00	1.41	1.95
37	.013	.046	.132	.310	.594	1.00	1.41	1.95
38	.014	.047	.133	.312	.596	1.00	1.41	1.95
39	.014	.047	.135	.314	.598	1.00	1.41	1.95
40	.014	.048	.136	.316	.600	1.00	1.41	1.95
41	.015	.049	.137	.318	.602	1.00	1.41	1.95
42	.015	.050	.138	.320	.604	1.00	1.41	1.95
43	.015	.051	.140	.321	.606	1.00	1.41	1.95
44	.016	.051	.141	.322	.608	1.00	1.41	1.95
45	.016	.052	.142	.323	.609	1.00	1.41	1.95
46	.016	.053	.143	.325	.610	1.00	1.41	1.95
47	.016	.053	.144	.326	.612	1.00	1.41	1.95
48	.017	.054	.145	.328	.614	1.00	1.41	1.95
49	.017	.055	.146	.330	.616	1.00	1.41	1.95
50	.017	.055	.147	.331	.618	1.00	1.41	1.95
51	.018	.056	.148	.333	.620	1.00	1.41	1.95
52	.018	.057	.150	.334	.621	1.00	1.41	1.95
53	.018	.057	.151	.336	.623	1.00	1.41	1.95
54	.018	.058	.152	.338	.624	1.00	1.41	1.95
55	.018	.059	.153	.340	.626	1.00	1.41	1.95
56	.019	.059	.154	.341	.627	1.00	1.41	1.95
57	.019	.060	.155	.343	.629	1.00	1.41	1.95
58	.019	.061	.156	.344	.630	1.00	1.41	1.95
59	.019	.061	.157	.346	.632	1.00	1.41	1.95
60	.020	.062	.158	.347	.633	1.00	1.41	1.95
61	.020	.063	.160	.349	.635	1.00	1.41	1.95
62	.020	.063	.161	.350	.636	1.00	1.41	1.95
63	.020	.064	.162	.351	.638	1.00	1.41	1.95
64	.021	.065	.163	.353	.639	1.00	1.41	1.95

TEMP °F	SETTLING VELOCITY IN FT/SEC							
	VFS	FS	MS	CS	VCS	VFG	FG	MG
65	.021	.065	.165	.354	.640	1.00	1.41	1.95
66	.021	.066	.166	.356	.641	1.00	1.41	1.95
67	.021	.067	.167	.357	.643	1.00	1.41	1.95
68	.022	.067	.168	.359	.644	1.00	1.41	1.95
69	.022	.068	.170	.360	.646	1.00	1.41	1.95
70	.022	.069	.171	.361	.647	1.00	1.41	1.95
71	.022	.070	.172	.362	.649	1.00	1.41	1.95
72	.023	.071	.173	.363	.650	1.00	1.41	1.95
73	.023	.071	.175	.364	.652	1.00	1.41	1.95
74	.023	.072	.176	.365	.653	1.00	1.41	1.95
75	.024	.072	.177	.366	.655	1.00	1.41	1.95
76	.024	.073	.178	.367	.656	1.00	1.41	1.95
77	.024	.073	.180	.368	.657	1.00	1.41	1.95
78	.024	.074	.181	.370	.658	1.00	1.41	1.95
79	.025	.074	.182	.371	.659	1.00	1.41	1.95
80	.025	.075	.183	.373	.660	1.00	1.41	1.95
81	.025	.075	.184	.375	.661	1.00	1.41	1.95
82	.025	.076	.185	.376	.662	1.00	1.41	1.95
83	.025	.077	.186	.378	.663	1.00	1.41	1.95
84	.026	.077	.187	.380	.664	1.00	1.41	1.95
85	.026	.078	.188	.381	.665	1.00	1.41	1.95
86	.026	.078	.190	.383	.666	1.00	1.41	1.95
87	.026	.079	.192	.385	.667	1.00	1.41	1.95
88	.027	.079	.194	.386	.668	1.00	1.41	1.95
89	.027	.080	.195	.388	.669	1.00	1.41	1.95
90	.027	.080	.196	.390	.670	1.00	1.41	1.95
91	.028	.081	.197	.391	.671	1.00	1.41	1.95
92	.028	.081	.198	.392	.672	1.00	1.41	1.95
93	.028	.082	.199	.393	.673	1.00	1.41	1.95
94	.028	.082	.200	.394	.674	1.00	1.41	1.95

[1]From reference 7.

For Reynolds numbers, $\mathbb{R}$, less than 0.1, Stokes law gives

$$C_D = 24/\mathbb{R} \tag{2-03}$$

where

$$\mathbb{R} = w \cdot d/\nu \tag{2-04}$$

ν = kinematic viscosity of fluid

$\mathbb{R}$ = Reynolds number

For Reynolds numbers greater than 0.1 there is no simple expression for the drag coefficient relationship, and the following curve is utilized with equations 2.02 and 2.04 to calculate fall velocity by successive approximations.

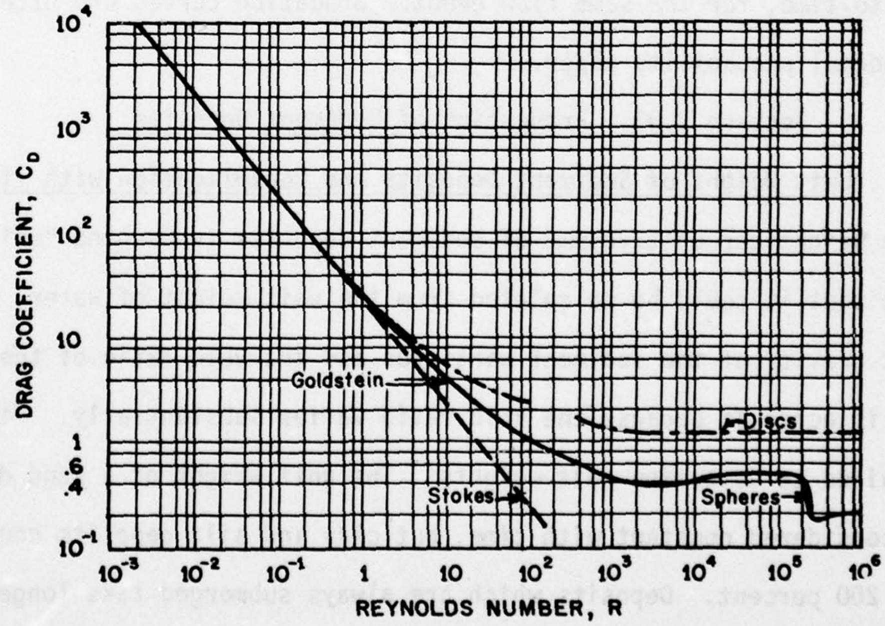

Fig. 2.01. Drag Coefficient of Spheres as a Function of Reynolds Number

f. Gradation Curve

An important property of the sediment sample is its gradation. Each sample will usually contain a range of grain sizes, and it is customary to break this range down into classes to determine the percentage by weight of the total sample contained in each class interval. The individual percentages are accumulated and the graph showing grain size vs. the accumulated percent of material that is finer than that grain size results in a gradation curve. This curve presents one set of statistics for that sample as shown in the following example (fig. 2.02). Gradation can change drastically from sample to sample. Furthermore, four different gradations are significant: the gradation of the suspended load, the gradation of the bed load, the gradation of the material comprising the bed surface and the gradation of material beneath the bed surface. These will all be significantly different, with respect to time, for the same flow event. Gradation curves are often plotted on log-normal probability paper.

Section 2.03. Properties of Sediment Deposits

a. Unit Weight of Sediment Deposits and Consolidation with Time

The weight per unit volume of sediment deposits is denoted "unit weight." The fact that it could be calculated from the unit weight of water, the specific gravity of the sediment particles and the void ratio of the sediment deposit is academic because the void ratio varies substantially. Field tests are required to determine unit weights. The unit weight of a sand deposit can be considered constant with time, but clay and silt deposits consolidate by over 200 percent. Deposits which are always submerged take longer to consolidate than those which are occasionally exposed to the air.

The following unit weights are often used when field data cannot be obtained.

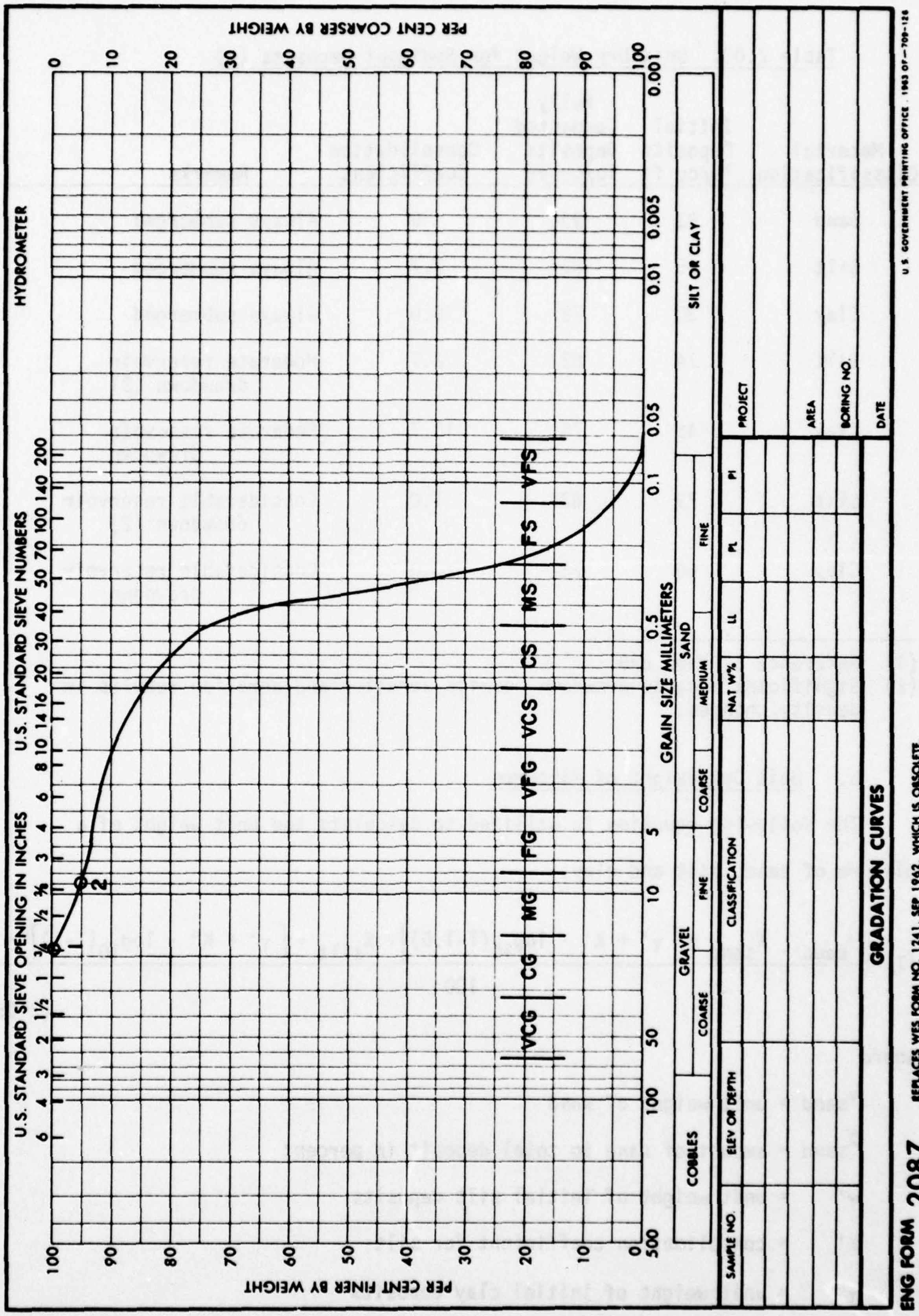

Fig. 2.02. Gradation Curve for a Bed Sample

Table 2.03. Unit Dry Weight for Sediment Deposits (1)

Material Classification	Initial Deposits lb/cu ft	Fully Compacted Deposits lb/cu ft	Consolidation Coefficient	Remarks
Sand	93	93	0	Always submerged
Silt	65	82	5.7	Always submerged
Clay	30	78	16.0	Always submerged
Silt	74	82	2.7	Moderate reservoir drawdown (2)
Clay	46	78	10.7	Moderate reservoir drawdown
Silt	79	82	1.0	Considerable reservoir drawdown (2)
Clay	60	78	6.0	Considerable reservoir drawdown

(1) Reference 1, page 829
(2) Significant because drawdown permits aeration and aeration results in density changes.

b. Unit Dry Weight of Mixtures

The following equation is utilized to calculate the unit weight of a mixture of sand, silt and clay.

$$\gamma_T = \frac{\gamma_{sand} \cdot \%_{sand} + \left[\gamma' + K' \cdot \log_{10}(T-1.0)\right] \cdot \%_{silt} + \left[\gamma'' + K'' \cdot \log_{10}(T-1)\right] \cdot \%_{clay}}{100} \qquad (2\text{-}05)$$

where

γ_{sand} = unit weight of sand

$\%_{sand}$ = amount of sand in total deposit in percent

γ' = unit weight of initial silt deposits

K' = consolidation coefficient for silt

γ'' = unit weight of initial clay deposits

K'' = consolidation coefficient for clay

T = life of deposit in years

$\%_{clay}$ = amount of clay in total deposit in percent

$\%_{silt}$ = amount of silt in total deposit in percent

γ_T = composite unit weight T years after deposition occurred

c. Impact on Water Quality

As one might suspect, those sediments having electrical charges, the clay material, play the most active role in water quality analysis. There is evidence that heavy metals, pesticides, hydrocarbons, radioactive wastes and other pollutants are attracted to these sediments and consequently zones of deposition may exhibit rather high concentrations of these pollutants.

Section 2.04. Properties of the Water-Sediment Mixture

a. Concentration

The dry weight of a sediment sample in milligrams divided by the weight of the water-sediment sample in liters is the common unit for sediment concentration. An alternate unit is parts of sediment per million parts of the water-sediment mixture. The first definition is preferred.

b. Sediment Load Terms

Sediment load refers to rates of sediment movement in the stream. Quantities should be expressed as tons per day and may be calculated from sediment concentration and water discharge in tons. Six different sediment load terms are encountered in sediment literature: suspended load, bed load, wash load, bed material load, measured load and unmeasured load. These terms go together in pairs to produce the total sediment load as follows:

$$
\begin{array}{ccccccc}
 & & \underline{\text{Based on mode of transport}} & & \underline{\text{Based on availability in stream bed}} & & \underline{\text{Based on method of quantifying}} \\
\text{Total load} & = & \begin{bmatrix} \text{suspended load} \\ + \\ \text{bed load} \end{bmatrix} & = & \begin{bmatrix} \text{wash load} \\ + \\ \text{bed material load} \end{bmatrix} & = & \begin{bmatrix} \text{measured load} \\ + \\ \text{unmeasured load} \end{bmatrix}
\end{array}
$$

Suspended load refers to those sediment particles which are transported entirely within the body of fluid with very little contact with the bed.

Bed load is that portion of the sediment load that moves essentially in contact with the bed. There is not a standard criteria for defining bed load. However, it is common to consider that load moving within two grain diameters of the bed is bed load. This point is not trivial when comparing one analytical technique with another. The quantity of bed load is very sensitive to thickness of the flow depth used in calculating it. However, it usually amounts to a small fraction of the total load. This definition recognizes that grain size alone is not sufficient to classify material as suspended load or bed load. Hydraulics of flow is also involved. Coarse material may move as suspended load in high energy flow and bed load in low energy flow. Suspended plus bed load will equal the total sediment load moving at that point in the stream.

Wash load, on the other hand, refers to that portion of the suspended load which is not found in the bed of the stream. That is, the gradation of the material in the stream bed is coarser than the gradation of material in the wash load. This is an important distinction for the later discussion on analytical techniques since all transport formulas

are based on the presence of material in the stream bed. The amount of wash load, on the other hand, depends solely on the supply of sediment entering the stream and cannot be calculated with transport formulas. (In many alluvial streams the wash load is finer than 0.0625 mm.)

Additional insight into the meaning of "wash load" was given by Dr. Hans Albert Einstein in reference 6 (pages 17-36) as follows: "either the availability of (sediment) material in the watershed or the transporting ability of the stream may limit the sediment load at a cross section. In most streams the finer part of the load, i.e., the part which the flow can easily carry in large quantities, is limited by its availability in the watershed. This part of the load is designated as wash load. The coarser part of the load, i.e., the part which is more difficult to move by flowing water, is limited in its rate by the transporting ability of the flow between the source and the section. This part of the load is designated as bed-material load."

Wash load is often thought of as the clay and perhaps silt material moving in the stream. However, in coarse bed streams, such as those with gravel cobble beds, wash load might also include sand sizes since these are limited by supply. One should be careful, however, to realize that the amount of sand on the stream bed at low water may be quite different from the amount at that same location during high water. Therefore, it is not possible to infer that the gradation of bed material is the same during a flood as it is during low water. In all likelihood, observations during high water would reveal the presence of much more sand material in the stream bed than is present in samples of bed material taken during low water. The companion term to wash load is bed material load. As the name implies, grain sizes in the bed material load are those grain sizes

which are also found in substantial quantities in the stream bed. Most analytical techniques concentrate on calculating the bed material load. This will oftentimes be only a small fraction of the total load moving, and yet it is the fraction that contributes the most information in channel morphology studies. The importance of bed material load is so great that most of the effort heretofore in the development of analytical techniques has centered on being able to calculate the bed material load moving in a stream.

The term, measured load, refers to all of the sediment load that can be measured with sampling equipment, which today is the suspended load to within 3 inches of the bed. Sampling equipment that measures the concentration of suspended material is highly developed relative to other sediment sampling equipment. It can operate over a range of depth or at a point; be hand held or operate from a cableway; and can measure a range of particle sizes up to 2 mm. This range of operation provides very acceptable results when one is interested in predicting total sediment yield from the watershed because that type of sampling would usually capture all but about 10 percent of moving sediment. However, in channel morphology studies the remaining 10 percent, the unmeasured load, is the most significant fraction.

The final term, unmeasured load, refers to that portion of the sediment load which is not measured and is usually the material either greater than 2 mm or moving within 3 inches of the bed. It is usually determined by calculations using the measured load as a guide. However, in coarse bed streams, the size of material moving in suspension will often exceed 2 mm, and the unmeasured load takes on more significance. In terms of total sediment yield, the unmeasured load may still be a very small amount.

However, in terms of channel aggradation or degradation trends, it will be a very significant load.

c. <u>Sediment Yield</u>

Sediment yield is the annual amount of sediment delivered from a drainage area, i.e., the total annual sediment load passing a gage on a stream. It is expressed in tons per year. A companion term is <u>unit sediment yield</u>, and this is the annual sediment yield divided by the drainage area - for example, tons/year/square mile. It is customary to correlate the annual sediment yield in tons with the annual water yield in acre feet as shown in the following figure. The relationship is usually satisfactory and the scatter that does exist will often exhibit a trend which can be used to further understand sediment production in the basin. (For example, the five high points in fig. 2.03 were excluded from the regression analysis because they occurred during five years starting in the dry 1930's whereas the remaining points are data from the late forties through the fifties and reflect current land use in the basin.)

Occasionally annual sediment yield is expressed in volume units, but this is not recommended. Transport equations require weight and sediment measurements and are presented as weight per unit time. To transfer from volume to weight requires data on unit weight of deposits which not only is difficult to determine but also changes with time.

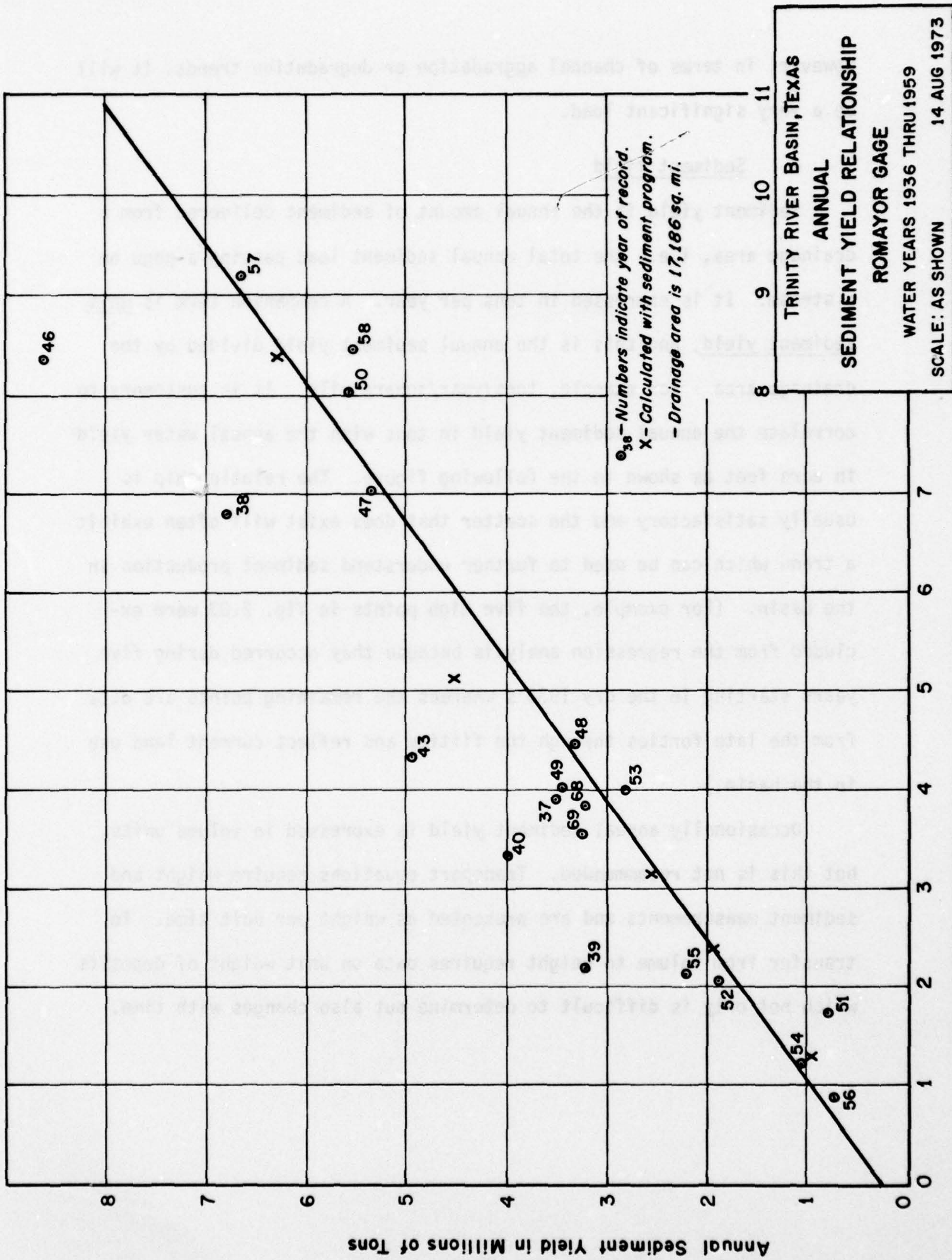

Fig. 2.03. Sediment Yield

Correlations between annual water yield and annual sediment yield indicate that a better approach for transferring sediment yield data from one basin to another is to relate the intensity of sediment production, tons/acre to the intensity of water production, cfs/acre, in the model basin, determine the water yield from the basin of interest and then transfer the sediment data through the observed correlation. Even when the basin of interest is ungaged, the water production can be approximated by techniques for transferring water data from gaged areas. Usually, water data is more readily available than sediment data.

Neither of these techniques establish the coarser load fraction of the sediment yield (i.e., medium sand and up) because these sizes move as a function of their availability in the stream bed and the hydraulics of flow. Fortunately the coarse material does not contribute substantially to the total sediment yield -- usually less than 5 or 10 percent. The importance of coarse material is discussed later in terms of channel regime.

Occasionally, units of volume are used to express sediment yield. This is particularly true when yield is calculated from measuring the accumulation of deposits in a reservoir. Two difficulties arise from this method: (1) the trap efficiency of the reservoir must be estimated and (2) the unit weight of deposits must be available so sediment volumes may be converted to weights for subsequent use in analytical studies. Trap efficiency is often very difficult to establish since one representative value must be determined for all magnitudes of flood events. This is discussed in more detail in Chapter 5. Unit weight of the actual deposits should be measured. The "typical" values of trap efficiency presented in this volume are not sufficiently accurate for use in such calculations.

CHAPTER 3. RIVER MORPHOLOGY

Section 3.01. Introduction

Rivers are dynamic not only in the sense that water in motion is dynamic but also in the sense that the size and alignment of their channels are continually changing. Work to set the fluid body in motion is provided by the potential energy gradient from the relief of the watershed. The river channel serves as a focal point for energy dissipation as flow from the entire watershed is collected there. In fixed bed hydraulics, energy is dissipated by friction, expansion and contraction losses as discussed in Volume 6, "Water Surface Profiles." In natural streams, however, part of the energy is used to transport the water, and part is used to transport the sediment material which moves in the water. The energy equation advanced in Volume 6 to describe the conservation of energy for flow within a fixed boundary does not adequately describe flow in a movable boundary because it does not provide a term for the energy required to transport the sediment material. At this point in time, no generally acceptable equation has been advanced to describe the movement of water-sediment mixture in a movable boundary.

Section 3.02. Lane's Equation of Dynamic Equilibrium

The fact is generally recognized, however, that nature maintains a delicate balance among the water-sediment mixture flowing in a natural

stream, sediment material forming the boundary of the stream channel, and the hydraulics of flow. In 1955 Lane summarized this balance with a qualitative statement which included the bed material load, Q_s, sediment size, D50, water discharge, Q, and energy gradient, S, as follows:

$$Q_s \cdot D50 \approx Q \cdot S \qquad (3\text{-}01)$$

He concluded that a channel is maintained in dynamic equilibrium by balancing changes in the sediment load and sediment size, with compensating changes in the water discharge and the energy gradient. Although many empirical equations have been developed around the variables in this expression, its main value is to show qualitatively the impact of changes in the water-sediment mixture on the behavior of the river channel conveyance system.

Section 3.03. Dynamic Equilibrium of Stream Bed Profiles

If the yield of bed material load should increase while the water discharge remains constant, according to expression 3-01, either the effective size of particles in the sediment load must decrease (the sediment load must become finer) or the system will be out of balance. A system which is out of balance in this manner will adjust itself by increasing the energy slope until the inflowing bed material load can be transported.

If, at some future time, the inflowing bed material load returns to its original value, the aggradation trend will cease and degradation will begin. Starting at the upstream end, sediment material will be removed from the stream bed and the slope will return to its original value.

Although this is a very simple illustration, it, and numerous variations,

can be observed in nature. Whereas the sediment load was assumed to increase in the above illustration, a more natural situation is for the water discharge to remain a constant value, the effective sediment size to be fairly constant and the energy slope to vary from point to point as in a natural river. Expression 3-01 indicates the sediment load must change when the energy slope does, and this requires sediment reservoirs from which material can be withdrawn as the energy gradient increases and into which material can be deposited when the energy gradient decreases. The stream bed provides those reservoirs, and the exchange of material involves, primarily, the coarser particles on and near the bed surface.

It will be convenient for subsequent discussions to identify a location where sediment material is being deposited as a <u>sink</u> and a location from which sediment material is being removed as a <u>source</u>. Part of the great complexity surrounding river behavior is the shifting of sources and sinks. Shifting can be related to two factors:

(1) The locations of sinks and sources are related to the location of hydraulic controls.

(2) If the volume of bed material at a source is exhausted, entrainment of material will shift to the next available location downstream and this may be a former sink.

As discussed in Volume 6, "Water Surface Profiles," the energy gradient along a stream is controlled by cross section shape and size in key locations called control sections. The energy gradient becomes steeper as flow approaches the control location. Reaching a maximum at the control, the energy gradient decreases, often abruptly, only to repeat the process at the next control downstream. Consequently, expression 3-01 would identify the control location as the downstream limit of a source.

During the passing of a large flood, more and more of the hydraulic controls become ineffective. Thus, new source/sink locations are established and old ones eliminated. Center bars may form where none had existed before simply because an unusually large percentage of the total flow was forced into the channel at one of these new control locations. Just upstream from a center bar, formed in this fashion, one will find the deeply scoured area that will become a new sink when normal flow conditions return.

Section 3.04. The River One Observes

Flood events pass quickly and a river channel seldom reaches an equilibrium condition during a single event. This complicates all attempts to correlate observed channel conditions with flow and sediment load. The river one observes reflects three magnitudes of flood events: (1) the low flow events which actually develop a low water channel which meanders within the river channel; (2) the normal flood events which mold the river channel; and (3) the most recent "superflood" event which molded the floor of the valley. It is important to recognize that conditions immediately following a superflood will reflect one extreme stage of equilibrium in the river, but quite a different stage of equilibrium will evolve after a sufficiently long period of normal years. This is particularly significant in levee design where the water surface profile for the highest equilibrium condition must be determined.

It is not safe to associate the superflood event with geological time. Certainly a Standard Project Flood (defined in Volume 5, "Hypothetical Floods") would be a superflood and the 100 year flood would also most likely qualify.

As used here, "superflood" identifies a flood event which is sufficiently large so its friction slope approximates that of the valley rather than the channel slope.

Expanding on the second factor presented above, the water discharge does not have to change for the locations of sources and sinks to shift. When all available sediment material is removed from a source area the water is left with an excess of transport capacity. Material previously deposited at a downstream location, perhaps, will become the first source for satisfying that excess. This constant shifting of sources and sinks would eventually smooth out the profile and produce a rather uniform movement of material if the water discharge became fairly constant. However, fluctuations in the water discharge hydrograph prevent this from happening.

Section 3.05. Rivers in Regime

a. Width, Depth and Slope Equations

Rivers, it is said, have four degrees of freedom: width, depth, slope, and meander pattern. The following equations are advanced to describe width, depth, and indirectly, the slope.

$$B = C_B^{\alpha_B} \tag{3-02}$$

$$D = C_D^{\alpha_D} \tag{3-03}$$

$$V = C_V^{\alpha_V} \tag{3-04}$$

where

B = width

C_B, C_D, C_V = empirical coefficients in the width, depth and velocity equations, respectively

D = depth

Q = representative water discharge

V = average velocity of flow

$\alpha_B, \alpha_D, \alpha_V$ = empirical exponents in the width, depth and velocity equations, respectively

To satisfy the principle of continuity it follows that:

$$\alpha_B + \alpha_D + \alpha_V = 1 \qquad (3\text{-}05)$$

and

$$C_B \cdot C_D \cdot C_V = 1 \qquad (3\text{-}06)$$

Investigations, reported by Leopold, et al.(1953), at 20 river cross sections in the Great Plains and the Southwestern United States resulted in the following average values:

$$\alpha_B = 0.26, \qquad \alpha_D = 0.40, \qquad \alpha_V = 0.34$$

It should be pointed out that these exponents are not necessarily transferable from one stream to another, or, for that matter, from one location to another on the same stream. Average values for exponents are given for 158 gaging stations in the United States in reference 12.

Undoubtedly, the experienced student of river geomorphology can gain considerable insight about the behavior of rivers by applying these regime equations. However, they confront the novice with some rather difficult basic questions, such as: "Where should one select a cross section for study? How does one determine a representative discharge? Why is sediment

load omitted from the equations? Why conduct a study at stream gage locations since they are not typical of the reach?" Nevertheless, this regime approach provides a point of view about the behavior of alluvial streams which should not be overlooked.

b. Meander Patterns

The fourth degree of freedom, the tendency to meander, is a natural fact; and, therefore, river engineers usually avoid designs which produce straight rivers. Canals are often straight or only slightly curved, but they remain so because of a high level of maintenance activity and because the water discharge is relatively constant.

The term "meandering" is used to refer to the S-curve pattern so typical of alluvial streams as well as to the movement of the river channel by the formation and destruction of bends. Accepting meander as an independent degree of freedom, the dynamics of the process become an outstanding consideration. Flood control with levees requires that the meandering tendency be controlled. At the present time, the meandering process is not well understood. "Channel loops form and migrate, bends lengthen, points extend, cutoffs occur and the process is repeated in such a manner that the width of the belt over which this takes place is rather constant in a river reach. . . .According to Krumbein and Sloss, it has been estimated that the average width of the meander belt is 15 to 20 times the width of the stream."[1] Levees are usually located within this meander belt.

Constraining the natural tendency of the channel to meander impacts on the behavior and sediment transport capacity of the river. This is not understood well enough to present even a qualitative analysis of the problem.

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[1]Reference 2, p. I-17.

However, it seems that if the channel is free to shift laterally, aggradation trends due to deposition of the coarser sands are offset by the river's freedom to select a location through smaller particle sizes. The point bar that results becomes a sink for the coarser sands. When the freedom to make such shifts is taken away because of bank stabilization, the coarser sands deposit on the stream bed, rather than point bars, with a resulting aggradation trend. When designing levees, one should consider the consequence of having to raise the levee at some future time to just maintain the capacity to pass the design flood. The implication is that a well-designed data collection program is essential.

Modification of the meander pattern by constructing cutoffs is a design consideration. However, equation 3-01 indicates the slope of a stream will not change unless either the water discharge, sediment load or effective grain size of material being transported is changed. Therefore, one might be skeptical about affecting a permanent lowering of the water surface profile by the construction of cutoffs.

The study of meander patterns involves the analysis of long reaches of rivers. Permanent controls need to be located, if available, to identify these reaches. An artificial control established at one location can impact on the meander pattern of the river channel at downstream locations. It is important, therefore, to design over long reaches and implement these designs to insure that construction at one point does not cause undesirable conditions to develop at some downstream point.

Section 3.06. Dominant Discharge

The possibility of selecting one representative water discharge that can be considered to have a dominant effect on river regime is very attractive, not from the standpoint of basing all studies of river behavior on that flow, but from the point of view that such a representative discharge offers a beginning point for studies.

Whereas the concept appears to be sound:

> "There is not general agreement on the proper value or method of determining this discharge. Carlston concluded that the dominant discharge which partially controls meander wavelength lies between the mean annual discharge and mean of the maximum monthly discharges. He also states there is some evidence that slope controls the meander wavelength. On the basis of logical reasoning that the dominant channel-forming discharge should be based on the time-duration-weighted bed-material-sediment transport capacity of the streamflow, an analysis of this type for the Arkansas River at Little Rock was conducted by the U.S. Army Engineer Division, Southwestern, Dallas, Texas. This study indicated that the dominant discharge covers a range from about 125,000 (half bank-full) to 175,000 cfs, or about three times the mean annual flow of 48,000 cfs."[2]

Another approach for determining dominant discharge was presented by Johnson in a paper entitled "Current Dutch Practice for Evaluating River Sediment Transport Processes," reference 13. It involves the development of

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[2] Reference 2, p. II-20.

a diagram depicting the total amount of sediment being transported during each interval of stage experienced at a gage and the calculation of the first moment about the abscissa to locate the dominant water level. The dominant discharge is associated with this water level by using a stage-discharge rating curve. A sample K-diagram is shown in the following figure.

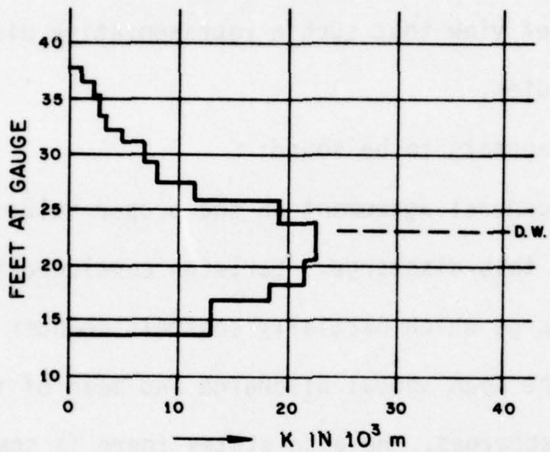


Fig. 3.01. K-Diagram

The abscissa, K, is calculated as follows:

$$K = \frac{m \cdot G \cdot p}{h \cdot \Delta h} \qquad (3\text{-}07)$$

where G = bed load transport, m^3/day

h = gage height

K = sediment load weighted by flow depth and class interval

m = time interval in days during which stage was within the class interval, Δh

Δh = class interval assigned to depth scale

The dimensionless coefficient, p, is defined as follows:

$$p = 1 + \left[\frac{0.25 \cdot B \cdot d^{3/2} \cdot \sqrt{g \cdot \sigma}}{G}\right]^{2/3} \quad (3\text{-}08)$$

where

B = width of river channel at the water surface, meters

d = effective grain size diameter in the bed load (d_{50}), meters

g = acceleration of gravity, meters/sec^2

G = bed load transport, units of m^3/second

p = a constant related to the least energy consumption hypothesis (reference 15)

σ = $(\rho_s - \rho)/\rho$ (3-09)

ρ = density of water

ρ_s = density of sediment particles

The bed load may be determined in a variety of ways. The analytical procedure proposed by Johnson is the Meyer-Peter and Muller equation. Reference 14 discusses this equation, and a brief summary is presented here.

The original form of the Meyer-Peter and Muller formula, in metric units, for a rectangular channel is

$$\gamma \cdot \frac{Q_B}{Q} \left(\frac{K_B}{K_G}\right)^{3/2} h \cdot s = 0.047 \cdot \gamma_s'' \cdot d + 0.25 \left(\frac{\gamma}{g}\right)^{1/3} G_1''^{\,2/3} \quad (3\text{-}10)$$

where

d = effective grain size of bed material

g = acceleration of gravity, m/sec^2

G" = bed load transport in metric tons/sec/meter of width (submerged weight)

h = water depth, m

Q = total, water discharge, liters/sec

Q_B = that portion of the total discharge which is responsible for the bed load transport, liters/sec

K_B = the Strickler roughness coefficient for the bed in $m^{1/3}$/sec

K_G = the grain roughness in $m^{1/3}$/sec

S = slope (dimensionless)

γ = specific weight of water, metric tons per m^3

γ_s'' = submerged specific weight of sediment particles $(\gamma_s - \gamma)$, metric tons/m^3

The relationship between specific weight and density is

$$\rho = \gamma/g \tag{3-11}$$

Rearranging terms in equation 3-10 leads to the following

$$G'' = 8 \cdot \gamma_s'' \cdot d^{3/2} \cdot \sqrt{g \cdot \rho} \cdot \left[\frac{Q_K \cdot h \cdot S}{\sigma \cdot d} - 0.047\right]^{3/2} \tag{3-12}$$

where

$$Q_K = \frac{Q_B}{Q}\left(\frac{K_B}{K_G}\right)^{3/2} \tag{3-13}$$

As expressed in equation 3-12, the units of bed load transport are metric tons/sec/meter of stream channel width, submerged weight. Converting this load to metric tons/sec, submerged weight is accomplished by multiplying by the stream channel width, B.

$$G' = 8 \cdot \gamma_s'' \cdot B \cdot d^{3/2} \sqrt{g \cdot \rho} \left[\frac{Q_K \cdot h \cdot S}{\sigma \cdot d} - 0.047\right]^{3/2} \tag{3-14}$$

In English units bed load transport is expressed as lbs/sec, dry weight. Changing from submerged to dry weight is accomplished by including the ratio γ/γ_s'' in equation 3-14, and redefining the units of variables as follows.

B = water surface width in channel, ft

d = effective grain size (d_{50}), in ft

g = acceleration of gravity, fps

G = bed load transport, tons/day dry weight

h = water depth, ft

Q_K = dimensionless coefficient

S = slope, ft/ft

γ = specific weight of water, lb/ft^3

γ_s = specific weight of sediment particles, lb/ft^3

$\gamma_s'' = \gamma_s - \gamma$

$\sigma = \gamma_s''/\gamma$ or $(\rho_s - \rho)/\rho$ = dimensionless coefficient

$$G' = 8 \cdot \gamma \cdot B \cdot d^{3/2} \cdot \sqrt{g \cdot \rho} \left[\frac{Q_K \cdot h \cdot S}{\sigma \cdot d} - 0.047\right]^{3/2} \qquad (3\text{-}15)$$

An even more common set of English units for bed load transport is tons/day, dry weight

$$G = 43.2 \cdot G' \qquad (3\text{-}16)$$

In evaluating Q_K it is necessary to determine how much of the total water discharge is used to transport the bed load. This is the water moving in the channel

$$Q_B = K_B \cdot A_B \cdot R_B^{2/3} \cdot S^{1/2} \qquad (3\text{-}17)$$

and

$$K_B = \frac{1}{n_B} \qquad (3\text{-}18)$$

A_B = cross sectional area for channel flow, $B \cdot h$

R_B = hydraulic radius of flow on channel bed, A/B

n_B = channel n-value includes grain and form roughness

The grain roughness may be calculated with the Strickler equation as

$$K_G = \frac{26}{d_{90}^{1/6}} \tag{3-19}$$

where

d_{90} = grain size for which 90 percent of material is finer

and $n_G = 1/K_G$ (metric) $= 1.486/K_G$ (English)

Taking the first moment of the K-diagram about the abscissa involves

$$DW = \frac{\sum^{I} K \cdot \Delta h \cdot h}{\sum^{I} K \cdot \Delta h} \tag{3-20}$$

where

K = calculated with equation 3-07 for each class interval of depth

Δh = the class interval assigned to depth

h = distance from the midpoint of Δh to the abscissa

I = the total number of class intervals

$$Q_D = f(DW) \tag{3-21}$$

The dominant discharge, Q_D, is read from a stage-discharge rating curve. Note that this value can change from year to year. Its only advantage is to aid in simplifying the early phases of studies and it should not replace the type of analysis, discussed subsequently, which uses a hydrograph of flow.

Section 3.07. The Impact of Tributaries on the Stream Bed Profile

Tributaries fall into two classes: (1) those transporting sediment that is finer than the bed load of the main stem, and (2) those having bed load material equal to or coarser than that of the main stem. The first type will assist the main stem in transporting bed material, resulting in channel degradation and a decrease in slope downstream from the confluence. The second type will exhibit the opposite trend with the confluence area serving as a sink for deposition of bed load until a flood on the main stem removes it.

It is important to note that the river one observes reflects a balance among the terms in expression 3-01, <u>especially</u> downstream from a tributary. When man regulates the main stem flow by a dam, the flow duration curve changes, which changes the dominant water discharge on the main stem. However, the tributary continues to bring in its same bed material load. Equilibrium is upset and the main stem often exhibits an aggradation trend. This trend results in increasing water surface profile elevations and must be taken into account in the design of levees or the acquisition of lands to permit project operation.

Section 3.08. The Importance of Natural Levees

The typical ground profile across many natural streams shows the ground surface to slope away from the channel in both directions.

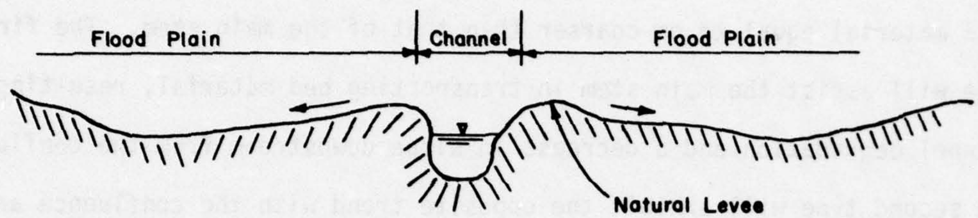


Fig. 3.02. Typical Cross Section Shape

The high ground adjacent to the channel is referred to as a "natural levee" since it is the result of sediment depositing during flood events as water flows out of the channel. The formation of natural levees plays a very significant role in the overall development of a river which is undergoing aggradation. Unfortunately, flow hydraulics associated with the problem are highly three-dimensional, and analytical procedures are not available to study the problem.

Qualitatively, one impact of maintaining a channel in a fixed location appears to be the continuing increase in height of the natural levees. This results in increasing the channel capacity to the point where the equilibrium between flow depth, width and velocity is upset. A consequence is the development of deep scour where the flow is confined and the subsequent deposition forming a center bar where the first expansion occurs downstream.

CHAPTER 4. COLLECTION AND ANALYSIS OF DATA

Section 4.01. Introduction

Data collection in alluvial streams involves sampling the boundary as well as properties of the water-sediment mixture that is flowing. Most data collection programs are designed to determine the annual weight of suspended sediment which requires measuring water discharge and sediment concentration. This level of information is essential for calculating sediment yield of the watershed. In addition to the suspended sediment load, sampling programs should periodically provide data on the amount of bed load moving. Particle size distribution in the suspended load, in the bed load, and in the bed surface as well as profiles along permanent sediment ranges should also be provided. If degradation studies are contemplated, sampling measurements should include the particle size distribution of material beneath the bed surface. All measurements of sediment loads should include water temperature and a water discharge measurement. Occasional measurements of water surface slopes are desirable. Each of these types of data is discussed in the following paragraphs.

Section 4.02. Suspended Load Measurements

a. Vertical and Lateral Distribution of Sediment

To calculate sediment discharge it is necessary to define the vertical and lateral distribution of concentrations in the cross section

and the variation of the mean concentration with time. If this distribution can be defined, sediment samples may be collected routinely at a single vertical in the cross section and the mean concentration calculated by the use of an index. Periodically, the distribution index should be revised by collecting a comprehensive set of data at many verticals. Oftentimes the distribution index will vary with water discharge, therefore it is essential to analyze a range of water discharges before assigning a distribution index. The season of the year is another variable which frequently correlates with the concentration distribution index.

The discharge-weighted mean concentration in a vertical generally is obtained from depth integrated samples collected with standard velocity-weighting samplers. The horizontal distribution of concentration may be obtained from these data. However, the determination of any vertical distribution of concentration requires point sample data in each vertical. The mean concentration in a cross section or a vertical is then computed by weighting the concentration of each individual point sample by the increment of discharge which it represents.

b. Mean Concentration for Section

Two techniques are available for calculating the discharge-weighted mean concentration in the cross section from the mean concentrations of the several sample verticals. If the sample vertical represents centroids of equal discharge (EDI method), the mean concentration is the average of the several verticals or is the mean of the composited samples, provided all samples are of the same volume. If, on the other hand, the sampled

verticals are uniformly spaced and the same vertical transient rate is used for all samples (ETR method), the mean concentration is the ratio of the total weight of sediment to the total weight of water-sediment mixture in all the samples.

c. Variation of Concentration with Time

Having obtained the discharge weighted concentrations for the cross sections, the next step in computing sediment discharge is to translate individual values of concentration into a continuous temporal concentration curve. This step may be reasonably simple if values for water discharge or sediment concentration do not vary greatly. However, at a new station, lack of knowledge of these trends together with the large number of variable conditions affecting sediment erosion and transport requires an intensive sampling program, and successful station operation requires continual modification of the sampling program to obtain the best results commensurate with a reasonable expenditure of time and effort. In any case, concentration data should be interpreted and the temporal graph prepared by personnel who have an indepth knowledge of the sampling program, and of the physical and cultural environments affecting the stream regimen and sediment sources. A good understanding of the fundamentals of sediment transport is essential (9).

d. Calculation of Sediment Load from Concentration

The sediment concentration in a sample may be determined as the ratio of the weight of the sediment to the weight of the water-sediment mixture. Because of convenience in the laboratory, it is usually

expressed in parts per million and defined as the dry weight of sediment divided by the weight of the water-sediment mixture multiplied by one million. It is customary to publish concentrations as mg/l, however, so the values determined in the laboratory must be converted prior to computation of the sediment discharge. The equation for sediment discharge is as follows:

$$Q_s = Q \cdot C_s \cdot k \quad (4\text{-}01)$$

where

Q_s = the sediment discharge in tons per day

Q = the water discharge in cubic feet per second

C_s = concentration of suspended sediment in mg/l

k = coefficient which converts volume per second to weight per day as follows:

k = .0027 tons per day when Q is expressed in cubic feet per second or k = .0864 metric tons per day when Q is expressed in cubic meters per second.

e. <u>Conversion of Units</u>

Values of the conversion factor C for converting parts per million to milligrams per liter are given in the following table. When the concentration exceeds 16,000 ppm the following equation should be used to obtain equivalent mg/l.

$$C_s = C \cdot ppm \quad (4\text{-}02)$$

where

ppm = parts per million and

C_s = the concentration of suspended sediment in mg/l.

Table 4.01. Conversion Factors, C, for Sediment Concentration: Parts Per Million to Milligrams Per Liter[1]

(The factors are based on the assumption that the density of water is 1.000 (plus or minus 0.005), the range of temperature is 0° - 29° C, the specific gravity of sediment is 2.65, and the dissolved-solids concentration is less than 10,000 ppm. This table supersedes table 1 in Guy [1969]).

Concentration Range (ppm)	C	Concentration Range (ppm)	C
0 - 15,900	1.00	322,000 - 341,000	1.26
16,000 - 46,800	1.02	342,000 - 361,000	1.28
46,900 - 76,500	1.04	362,000 - 380,000	1.30
76,600 - 105,000	1.06	381,000 - 399,000	1.32
106,000 - 133,000	1.08	400,000 - 416,000	1.34
134,000 - 159,000	1.10	417,000 - 434,000	1.36
160,000 - 185,000	1.12	435,000 - 451,000	1.38
186,000 - 210,000	1.14	452,000 - 467,000	1.40
211,000 - 233,000	1.16	468,000 - 483,000	1.42
234,000 - 256,000	1.18	484,000 - 498,000	1.44
257,000 - 279,000	1.20	499,000 - 514,000	1.46
280,000 - 300,000	1.22	515,000 - 528,000	1.48
301,000 - 321,000	1.24	529,000 - 542,000	1.50

This table shows that concentrations expressed in mg/l are the same as ppm for values up to 16,000 ppm.

[1] United States Geological Survey, Techniques of Water Resources Investigations, "Computation of Fluvial-Sediment Discharge" by George Poterfield, U. S. Government Printing Office, 1972, p. 43.

f. Particle Size Analysis of the Suspended Sediment

A sufficient number of samples should be analyzed each year to determine representative values for particle size distribution in the water-sediment mixture. The accuracy of such analyses is dependent on, among other things, the quantity and physical characteristics being analyzed. The following table presents the quantity of sediment required for various methods of determining particle size distribution.

Table 4.02. Quantity of Sediment for Particle Size Analysis, in Grams (9)

Method	Minimum	Optimum
Dry sieve	50	100
Wet sieve	0.05	1.0
VA tube (1)	0.05	1.0 - 7.0
Pipet	0.8	3.0 - 5.0
BW tube (2)	0.5	0.7 - 1.3

Table 4.03 shows the type of data needed from suspended measurements. Of course, this amount of detail is not needed from every sample.

g. Correlation Between Concentration or Sediment Load and Water Discharge

Attempts to correlate sediment concentration with water discharge, even when using multiple linear regression in which other parameters such as water temperature or season of the year were included, have been unsuccessful. However, the mass of material moving, expressed in units of tons per day, is often correlated with water discharge to form a

Table 4.03. Summary Data of Suspended-Sediment Particle-Size Distribution, Clearwater River at Spalding, Idaho

Sieve Size (mm)	Date; Discharge (ft^3/sec); Concentration (mg/l)				
	01-19-74 28,000 144 1/	06-05-74 68,700 113	06-10-74 46,000 31	06-18-74 117,000 131	06-26-74 67,000 30
1.0	-	100.00	100.00	100.00	100.00
.71	-	99.65	98.96	98.74	99.07
.50	100.00	-	-	-	-
.35	-	92.01	77.68	86.73	89.44
.25	99.6	79.31	61.65	75.68	83.84
.18	-	67.99	52.24	66.79	80.48
.12	98.3	62.43	43.38	56.34	76.00
.09	-	56.53	35.07	47.33	70.16
.06	97.0	54.43	29.65	42.84	68.45
.03	89	-	-	-	-
.016	70	-	-	-	-
.008	54	-	-	-	-
.004	41	-	-	-	-
.002	36	-	-	-	-

1/ Conducted in Sacramento Sediment Laboratory, U.S. Geological Survey.

relationship known as a sediment load rating curve (fig. 1 of Appendix III). Often, the scatter of data is on the order of one log cycle. Nevertheless, many sediment studies require a relationship between the average sediment load and the water discharge, and it is possible to fit a curve through such data so the correct volume of sediment is produced given a specified water discharge hydrograph.

Sediment load rating curves are not always suited for use in calculating sediment yield because of the wide scatter of data. On the other hand, they are convenient and are oftentimes the only data available. Therefore, they are frequently used to estimate sediment yield for engineering projects.

Section 4.03. Bed Load Measurements

River engineers are skeptical about the adequacy of present techniques for producing satisfactory measurements of the bed load. In terms of total sediment yield, that portion of material contributed by bed load is usually small. Therefore, it has not been of a great deal of interest in the solution of practical problems in the past. Recent advances in analytical capability afforded by simulation techniques and the electronic computer make it possible to utilize bed load data in doing channel aggradation and degradation studies. In these studies it is the bed material load that causes channel problems. The USGS recently completed a three-year program of intensive data collection involving measuring the bed load for use in sediment distribution studies on the Clearwater and Snake River

arms of Lower Granite Reservoir (1972-1974). The following insight was obtained from that study.

The water sediment mixture contained material ranging from very fine sand to 256 mm cobbles. (For the purpose of this exercise, bed load is defined as that material moving within half a foot of the channel bed since that is the size of orifice in the sampler used in the data collection.) Two samples were collected at each of 10 verticals going across the river and this was repeated on the return trip making a total of 40 samples per measurement. Results showed that both the temporal and spatial fluctuation in bed load is greater than it is for suspended load, therefore, the concept of an index station and a reduced number of samples does not seem appropriate for measuring bed load. Table 4.04 shows typical information from measurements in this program. The Helley-Smith sampler utilized in this program performed very well when compared with a continuous belt bed load sampler in another stream. It is presently undergoing more intensive calibration at the Federal Inter-agency Sedimentation Project, St. Anthony Falls Hydraulic Laboratory, Minneapolis, Minnesota.

Bed load measurements without a corresponding particle size analysis are not useful. Techniques which demand information on the bed load movement also require a detailed gradation of the bed load itself.

Table 4.04. Summary Data of Bedload Particle-Size Distribution, Clearwater River near Spalding, Idaho

Sieve Size (mm)	Date; Discharge (ft^3/sec); Transport Rate (tons/day) 05-23-74 22,000 6.25	06-04-74 61,000 1,333 1/	06-06-74 80,000 191	06-12-74 60,000 356	06-17-74 124,000 1,136 1/	06-20-74 110,000 3,699	Composite 1974 2/
128	-	-	-	-	-	100.00	100.00
90	-	-	100.00	-	-	80.02	89.60
64	-	-	72.36	100.00	-	53.36	67.97
45	-	-	62.85	93.94	100.00	32.23	52.38
32	-	-	62.85	90.62	98.13	23.06	44.59
22.6	-	100.00	62.32	88.49	97.46	17.38	40.35
16	-	97.16	61.08	87.06	96.72	14.52	38.26
11.3	-	92.96	60.84	86.17	96.04	12.62	36.96
8	-	90.46	60.40	85.81	95.10	11.07	35.92
5.7	-	88.28	60.10	85.64	94.29	9.77	35.08
4	-	87.05	59.92	85.51	93.50	8.91	34.51
2.8	-	85.52	59.71	85.31	92.60	8.13	33.96
2	100.00	84.68	59.46	85.05	91.72	7.57	33.51
1.4	99.88	83.80	59.07	84.63	90.55	7.07	33.04
1.0	98.95	82.49	58.28	83.47	88.33	6.64	32.32
.71	94.50	73.90	55.58	74.34	78.68	5.76	29.02
.50	65.38	42.56	45.73	49.71	54.42	4.00	19.04
.35	27.13	20.80	31.14	24.90	30.07	2.14	9.60
.25	6.90	7.10	12.37	7.01	9.59	.63	2.89
.18	1.29	.68	1.97	.55	1.51	.10	.35
.12	.70	.26	.64	.21	.55	.05	.14
.09	.47	.13	.29	.12	.28	.03	.08
.06	.23	.06	.14	.06	.16	.02	.04
Pan	.00	.00	.00	.00	.00	.00	.00

1/ Computed from incomplete number of samples.

2/ Total sample weight = 189 pounds.

Section 4.04. Sediment Yield

a. Calculation of Sediment Yield

The best method for determining annual sediment yield is to accumulate the mean daily loads. Usually the published daily loads are suspended sediment only and have to be increased by 5 or 10 percent to include the unmeasured portion of sediment passing the gage.

As illustrated in fig. 2.03, Sediment Yield, the quantity of annual sediment yield correlates rather well with water yield. Therefore, calculating sediment yield from observed sediment loads will not necessarily produce the long term average or even a design value for sizing a reservoir. Therefore, a sediment load curve, such as presented in fig. 1 of Appendix III, should be integrated with the long term water discharge-duration curve to produce a design yield for a reservoir study.

Land use is a very important parameter in projecting sediment yield or transferring yield estimates from one basin to another.

Appendix III, entitled Corps of Engineers Methods for Predicting Sediment Yields, presents details of several approaches for estimating sediment yield.

Universal soil loss equation. Some attempts have been made to calculate sediment yield from rainfall, erodability of the soil, ground surface slope, length of overland flow, ground cover and erosion control practices. Reference 10 is one such example. This method utilizes the following equation:

$$Y_e = R_e \cdot K_e \cdot S \cdot L \cdot C_f \cdot P_e \qquad (4\text{-}03)$$

where

Y_e = potential sediment yield in tons/acre

R_e = the rainfall energy factor

K_e = erodability of the soil

S = slope of ground surface

L = slope length

C_f = cropping factor

P_e = erosion control factor

These terms appear to convey the important factors in the erosion process, and the resulting quantity of sediment depicts the soil loss potential of a specific small land area. However, sediment yield at a stream location encompasses more than just this soil loss potential. The eroded sediment material has to be transported through channels to an outflow point. Perhaps clays and silts in the outflow will correlate with soil loss potential calculated in the above manner, but the total yield of sediments from a drainage basin will depend primarily upon flow hydraulics and the availability of material in and near the stream channel or conveyance system.

b. Transferability of Sediment Yield Data

As one might suspect, the scatter in data becomes much less when relating annual sediment yield to annual water yield than it is at the same gage for daily values of sediment load vs. water discharge. Consequently, annual sediment yield curves provide a very satisfactory mechanism for transferring sediment data from one basin to another or from one point to another in the same basin. This procedure is not satisfactory where there is a substantial difference in land use between the two gage sites. Land use in this sense is meant to be the percentage of land in the basin that is occupied by forest, pasture, row crops or by other uses. The following figure illustrates transferring sediment yield data between two points in the same basin by using

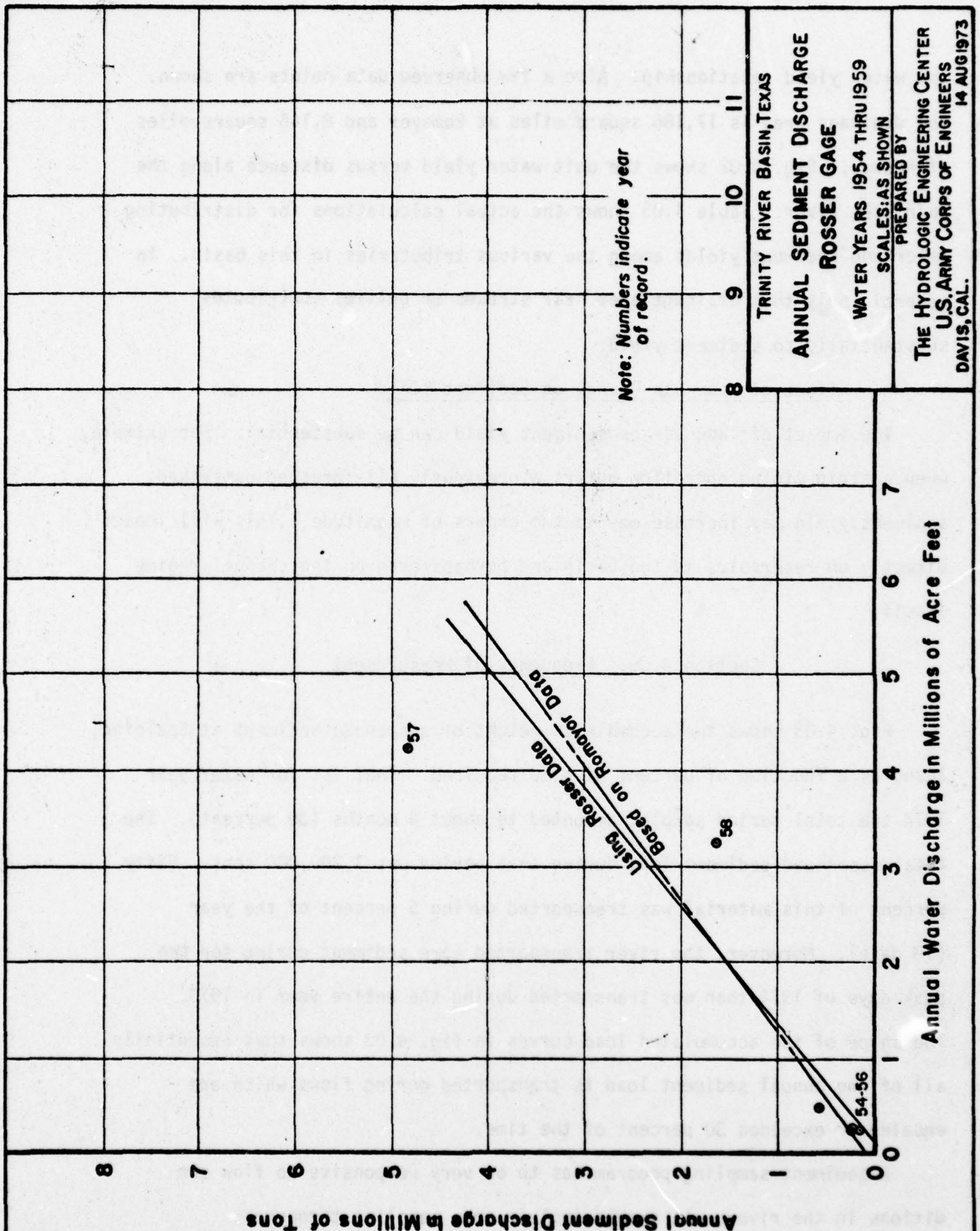


Fig. 4.01. Transferring Sediment Yield Data in a Basin

the water yield relationship. Also a few observed data points are shown. The drainage area is 17,186 square miles at Romayor and 8,146 square miles at Rosser. Fig. 4.02 shows the unit water yield versus distance along the main stem river. Table 4.05 shows the actual calculations for distributing water and sediment yields among the various tributaries in this basin. In general, only that drainage area near streams or gullies contributes substantially to sediment yield.

c. Effect of Land Use Change on Sediment Yield

The impact of land use on sediment yield can be substantial. For example, when a strip mining operation enters a previously all-forested watershed, sediment yield may increase one to two orders of magnitude. This will impact directly on reservoirs in the basin and perhaps even on the channel regime itself.

Section 4.05. Frequency of Measurement

Fig. 4.03 shows the accumulated weight of suspended sediment at Spalding, Idaho as a function of percent of time required. That is, for water year 1974 the total period sampled amounted to about 4 months (30 percent). The total suspended sediment load during that period was 1,200,000 tons. Fifty percent of this material was transported during 5 percent of the year (18 days). Moreover, the river transported more sediment during the two peak days of 1974 than was transported during the entire year in 1973. The shape of the accumulated load curves in fig. 4.03 shows that essentially all of the annual sediment load is transported during flows which are equaled or exceeded 30 percent of the time.

A sediment sampling program has to be very responsive to flow conditions in the river. It should include some sampling throughout

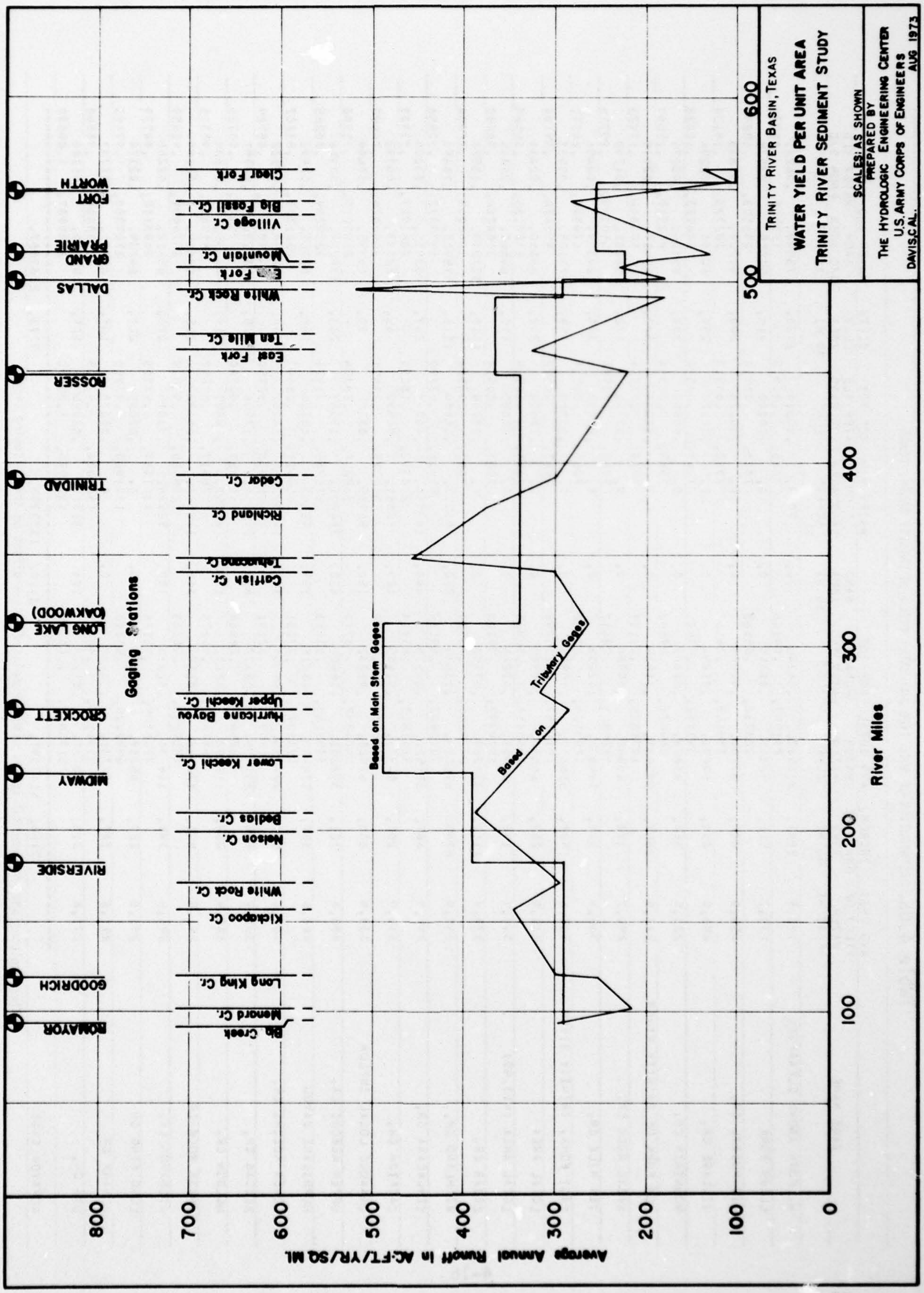


Fig. 4.02. Distribution of Unit Water Yield

Table 4.05. DISTRIBUTION OF SOIL TYPE AND WATER YIELD IN TRINITY BASIN, TEXAS

GAGE NAME	AVG UNIT YIELD OF WATER AF/SQ MI	INCREM. DRAINAGE AREA SQ MI	AVG TOTAL WATER YIELD AC-FT*	%OF TOT ROMAYOR WATER YLD ÷100*	SAND AREA SQ MI	WATER YLD FROM SAND AREA AC-FT*	%OF TOT WATER YLD FROM SAND ÷100*	SILT/ CLAY AREA SQ MI	WATER YLD FROM S/C AREA AC-FT*	%OF TOT WATER YLD FROM S/C ÷100*
W. FORK ABOVE CLEARFORK	100,9	2097.	211587.	.04146	70.	7063.	.00514	1720.	173548.	.06221
			211587.	.04146		7063.	.00514		173548.	.06221
CLEAR FORK	139,7	518.	72365.	.01418	0.	0.	.00000	415.	57975.	.02078
			283952.	.05563		7063.	.00514		231523.	.08299
BIG FOSSIL CR.	256,0	200.	51200.	.01003	0.	0.	.00000	200.	51200.	.01835
			335152.	.06567		7063.	.00514		282723.	.10134
VILLAGE CR.	256,0	250.	64000.	.01254	0.	0.	.00000	250.	64000.	.02294
			399152.	.07821		7063.	.00514		346723.	.12428
MOUNTAIN CR.	223,5	384.	85824.	.01682	0.	0.	.00000	384.	85824.	.03076
			484976.	.09502		7063.	.00514		432547.	.15504
ELM FORK OF TRINITY RIVER	223,5	2657.	593839.	.11635	0.	0.	.00000	302.	67497.	.02419
			1078815.	.21137		7063.	.00514		500044.	.17923
WHITE ROCK CR.	290,7	172.	50000.	.00980	0.	0.	.00000	172.	50000.	.01792
			1128816.	.22117		7063.	.00514		550045.	.19716
TEN MILE CR.	365,6	340.	124304.	.02435	0.	0.	.00000	340.	124304.	.04456
			1253120.	.24552		7063.	.00514		674349.	.24171
EAST FORK, TRINITY RIVER	365,6	1528.	558637.	.10945	0.	0.	.00000	758.	277125.	.09933
			1811757.	.35498		7063.	.00514		951474.	.34104
LOCAL AREA	339,9	202.	68660.	.01345	0.	0.	.00000	202.	68660.	.02461
			1880416.	.36843		7063.	.00514		1020133.	.36565
LOCAL AREA (413,95)	339,9	190.	64581.	.01265	0.	0.	.00000	190.	64581.	.02315
			1944997.	.38108		7063.	.00514		1084714.	.38880
CEDAR CR.	339,9	1110.	377289.	.07392	0.	0.	.00000	1110.	377289.	.13523
			2322286.	.45500		7063.	.00514		1462003.	.52404
RICHLAND CR.	339,9	2048.	696115.	.13639	270.	91773.	.06684	1518.	515968.	.18494
			3018402.	.59139		98836.	.07199		1977972.	.70898
TEHUACANA CR.	339,9	687.	233511.	.04575	440.	149556.	.10893	247.	83955.	.03009
			3251913.	.63714		248392.	.18091		2061927.	.73907
CATFISH CR.	339,9	250.	84975.	.01665	185.	62881.	.04580	65.	22093.	.00792
			3336888.	.65379		311273.	.22671		2084020.	.74699
OAKWOOD LOCAL INFLOW	339,9	200.	67980.	.01332	150.	50985.	.03713	50.	16995.	.00609
			3404868.	.66711		362258.	.26384		2101015.	.75308
UPPER KEECHI CR.	488,6	721.	352281.	.06902	438.	214007.	.15587	283.	138274.	.04956
			3757148.	.73613		576265.	.41971		2239289.	.80265
HURRICANE BAYOU	488,6	357.	174430.	.03418	189.	92345.	.06726	168.	82085.	.02942
			3931579.	.77031		668611.	.48697		2321374.	.83207
LOWER KEECHI CR.	488,6	539.	263355.	.05160	395.	192997.	.14057	144.	70358.	.02522
			4194934.	.82191		861608.	.62754		2391732.	.85729
BEDIAS CR.	388,9	850.	330565.	.06477	635.	246951.	.17986	215.	83613.	.02997
			4525499.	.88668		1108559.	.80740		2475346.	.88726
NELSON CR.	388,9	289.	112392.	.02202	175.	68057.	.04957	114.	44335.	.01589
			4637891.	.90870		1176617.	.85697		2519680.	.90315
WHITE ROCK CR.	291,8	590.	172162.	.03373	385.	112343.	.08182	205.	59819.	.02144
			4810053.	.94243		1288960.	.93879		2579499.	.92459
KICKAPOO CR.	291,8	398.	116136.	.02275	180.	52524.	.03825	218.	63612.	.02280
			4926189.	.96518		1341484.	.97705		2643112.	.94739
LONG KING CR	291,8	227.	66239.	.01298	0.	0.	.00000	227.	66239.	.02374
			4992428.	.97816		1341484.	.97705		2709350.	.97113
MENARK CR	291,8	167.	48731.	.00955	0.	0.	.00000	167.	48731.	.01747
			5041158.	.98771		1341484.	.97705		2758081.	.98860
BIG CR.	291,8	215.	62737.	.01229	108.	31514.	.02295	109.	31806.	.01140
			5103895.	1.00000		1372998.	1.00000		2789887.	1.00000
ROMAYOR GAGE		17186.	5103895.		3620.	1372998.		9773.	2789887.	

*These columns show incremental values with accumulated values offset on the following line.

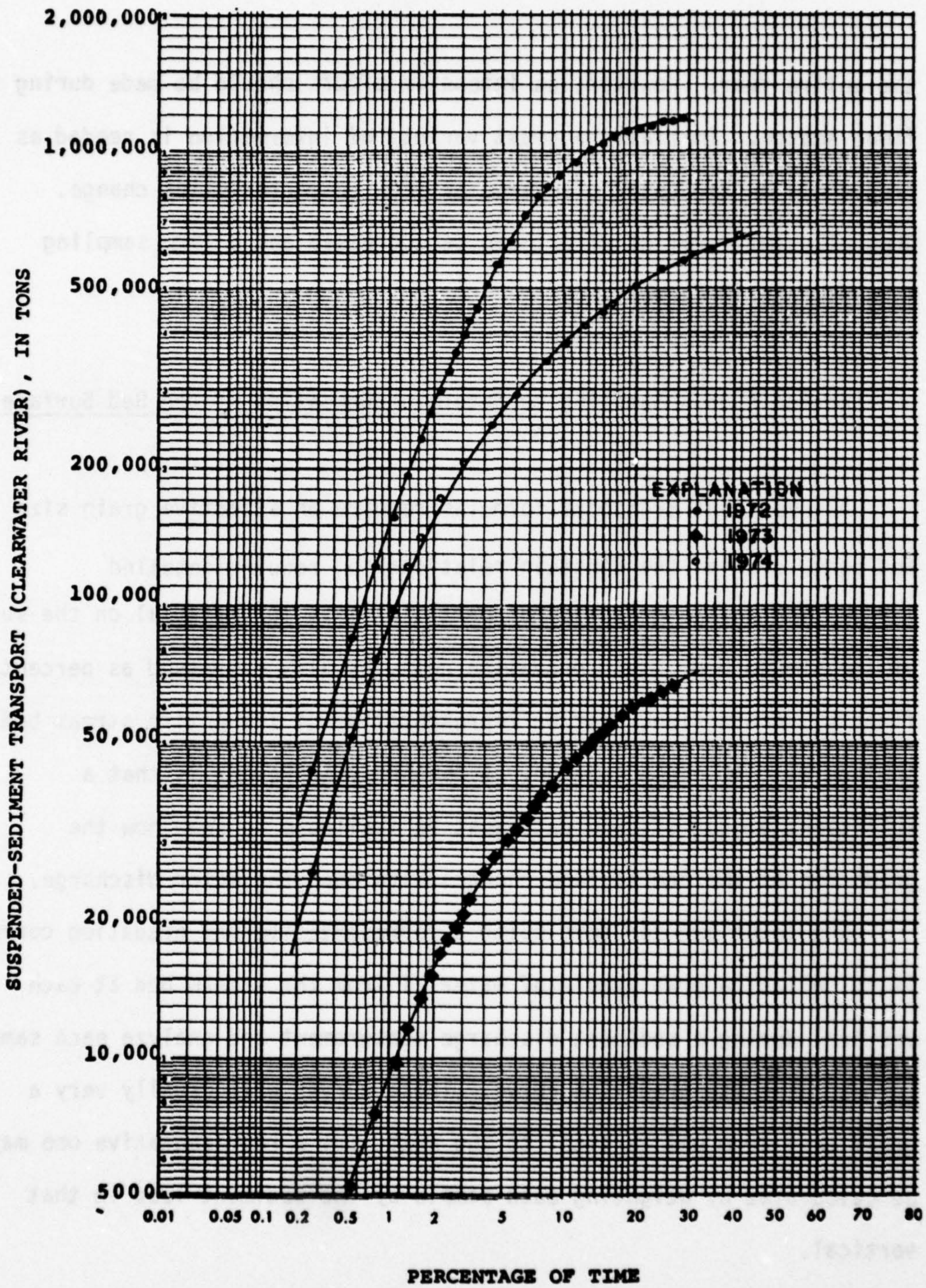


Fig. 4.03. Accumulative Suspended-Sediment Transport as a Function of Time, Clearwater River at Spaulding, Idaho, taken from basic data prepared by U.S. Geological Survey, Boise, Idaho.

the entire year. However, an intensive effort should be made during the flood season. Initially a great variety of information is needed as frequently as the water discharge or flow characteristics change. Gradually the level of effort can be decreased and a firm sampling schedule can be established.

Section 4.06. Sampling to Determine Gradation of the Bed Surface

All sediment transport formulas require an effective grain size and some, such as the Einstein relationship, require detailed information on the gradation of particle sizes for material on the surface of the stream bed. This gradation data, usually expressed as percent finer vs. grain size, must be representative of the entire stream bed surface at that cross section. A further requirement is that a sufficient amount of such data must be available to show how the gradation of the bed surface changes with changing water discharge.

One technique for developing a representative bed gradation curve is to collect a grab sample of material from the stream bed at each vertical during a sediment discharge measurement and analyze each sample to determine its gradation curve. These curves will usually vary a great deal from one vertical to the next, but a representative one may be calculated by weighting each sample by the sediment load in that vertical.

The bed gradation observed during low flow is not representative of the bed during a high flow event. Bed gradation changes in response

to the sizes of sediment which are moving as bed material load, and the size of the bed material load varies with water discharge and the supply of material that is available. The supply of material is controlled by upstream sources and sinks. Flow duration is an important factor for determining whether a source of material is exhausted or not and, consequently, this affects the bed gradation. Therefore, bed gradation samples should be taken for a wide range of water discharges and flow durations. Data from each event may be analyzed as discussed above.

It is often impossible to collect bed samples during a flood event. Two techniques are presented for circumventing this problem. The first, and least expensive, is to sample at selected locations during low flow periods; and the alternative is to collect samples of bed load, suspended load, water discharge, water velocity, water depth, slope and width, and to calculate the gradation of bed material that is required to transport the measured loads. These techniques are presented in the following paragraphs.

Recent experience with the first technique on coarse-bed streams indicates that samples of material near the water's edge during periods of low flow are representative of the gradation in the stream bed only during periods of low flow. The gradation of samples taken at about midway between the bed and the top bank agreed better with calculated bed gradations in the simulation model during flood flows when the inflowing sediment load was just transported without scour or deposition of the bed.

Figure 4.04 entitled, Gradation of Bed and Bank Material, shows both measured and calculated bed gradation on the Scioto River, Ohio. In this case, the sediment load transported during flood discharges required a smaller effective diameter in the bed material than that transported during low flow events. In both cases the inflowing sediment load was just transported, in the simulation model, with neither scour nor deposition occurring. This comparison suggests that samples from the stream bed should be used when calculating sediment load for low flow events, but when calculating the load for high flow events, one should also consider samples from the stream bank if bed samples were not taken during high discharges.

The second technique for developing bed gradation data is to measure the total bed material load moving, to measure hydraulic parameters and to calculate the gradation of the bed surface that is required to transport that measured load.

Section 4.07.
Sensitivity of Transport Calculations to Bed Surface Gradation

It is desirable to have two samples at each cross section when utilizing the existing simulation models to calculate bed load transport from bed gradation and hydraulics of flow. However, in studies which extend over long distances such a data collection program would require too much investment. Efforts should be concentrated in one short reach with subsequent samples spaced sufficiently far apart to provide guidance in the calibration of the simulation model.

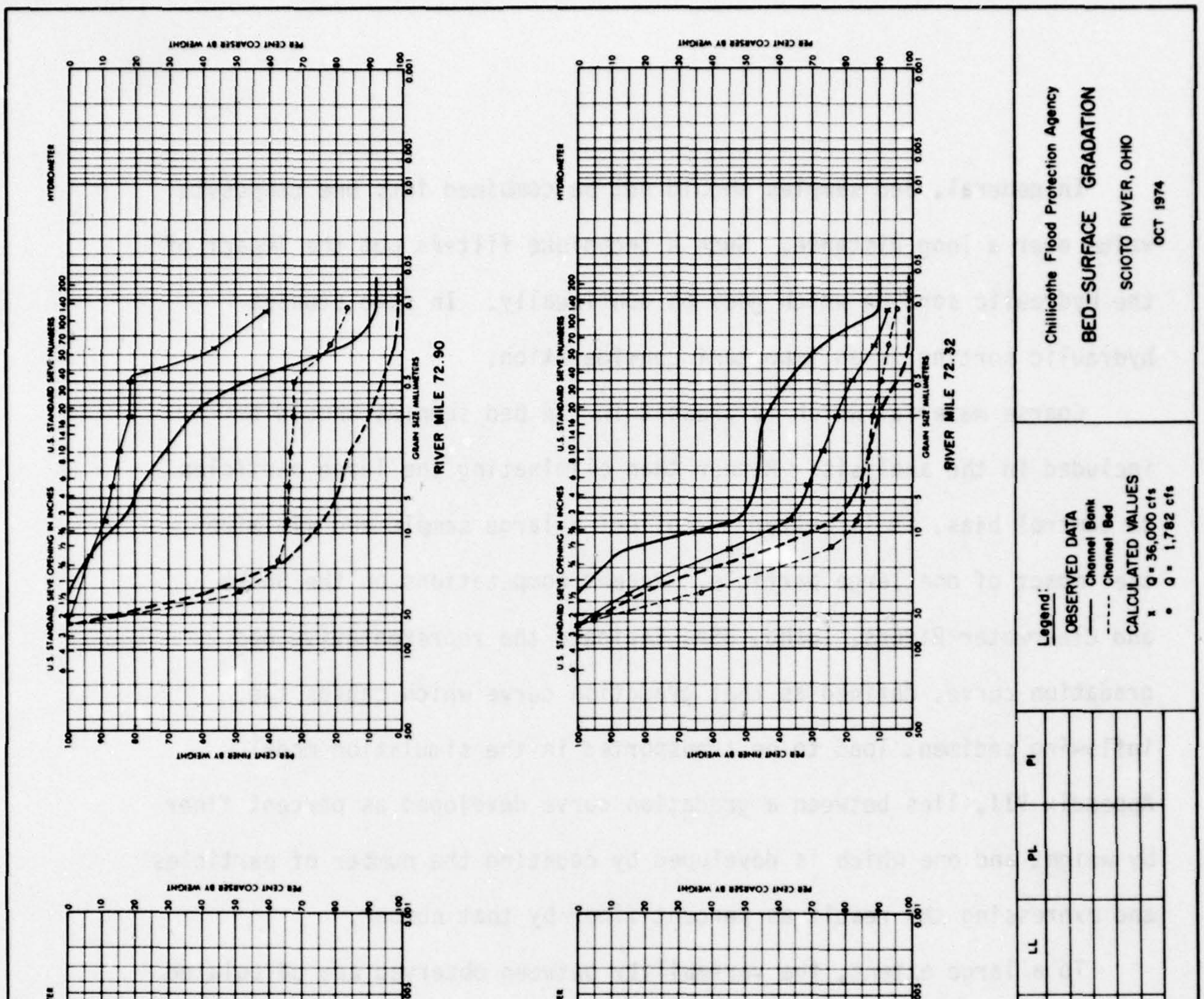


Fig. 4.04. Gradation of Bed and Bank Material

In general, bed samples should not be combined into one composite value over a long distance. Such a technique filters out the impact of the hydraulic sorting which goes on continually. In some studies hydraulic sorting is an important consideration.

Coarse material which is present in the bed samples should be included in the analysis. Rather than eliminating the large particles to control bias, it is better to collect a large sample and minimize the impact of one large particle. Recent computations on the Snake and Clearwater Rivers, Idaho, USA, indicate the representative bed gradation curve, defined as that gradation curve which causes the inflowing sediment load to be transported in the simulation model, Appendix VII, lies between a gradation curve developed as percent finer by weight and one which is developed by counting the number of particles and expressing the result as percent finer by that number.

To a large extent, the variability between observed and calculated bed material loads can be attributed to bed surface particle sizes which are not representative of the prototype condition. Sensitivity of calculated results to percentage of material in the bed is shown in the following table.

The first four columns are typical of the calculations required to determine the sediment transport capacity of the bed material load for a given hydraulic condition. The total observed bed material load was 6000 tons/day. Column 5 is included to illustrate the sensitivity of the calculated bed material load to the bed gradation curve.

For example, if the bed samples collected in the field misrepresent the amount of Very Fine Sand on the stream bed by only 1 percent, the resulting calculated bed material load would have been doubled for that size fraction. The larger grain sizes are not affected this much.

This sensitivity alone causes one to question values of bed material load calculated by transport functions. However, particle sizes up through medium sand move predominately as suspended load and can be sampled quite easily. As seen in table 4.06, this is the major portion of the total bed material load.

Section 4.08. Sampling Beneath the Bed Surface

Ordinary data collection programs do not address sampling of the sediment material beneath the bed surface. Those situations involving channel degradation and armoring require such information, however. Not only is the particle size analysis important, oftentimes the depth to bedrock is an important consideration.

The calculations for potential degradation and armoring are not as sensitive to the amount of material in the stream bed as sediment transport calculations are because fine material is not involved. However, it is probably the coarsest 2-3 percent of material in the natural stream bed which accumulates to form an armor layer and arrest degradation trends.

Table 4.06. Sensitivity of the Toffaleti Sediment Transport Formula to Gradation of the Bed Surface

Grain Size	Potential Transport Capacity(1) tons/day	Gradation of Bed Surface	Transport Capacity tons/day	1% Error in Bed Gradation
(1)	(2)	(3)	(4)	(5)
VFS	630000	.0046	2930	6300
FS	200000	.0053	1053	2000
MS	50000	.0370	1852	500
CS	7700	.0374	288	77
VCS	1150	.0643	74	11
VFG	310	.0387	12	3
FG	130	.0384	5	1
MG	60	.0833	5	1
CG	25	.08	2	0
VCG	10	.30	3	0
	(2)	.6890	6224	8893

Notes: (1) This is multiplied by the fraction of material on the bed surface to determine sediment load moving in tons/day.

(2) A summation of this column has no meaning.

The number and location of samples required for degradation studies are difficult and depend on the stream and the problem being analyzed. If the problem involves local scour, the bed samples should be taken within the expected scour zone. If the problem involves general channel degradation, the samples should be spaced out along the channel. The significance of even a few coarse particles should not be underestimated.

Some locations show sediment gradation curves which do not change with depth. Other locations show a distinct trend in the gradation of sediment material with respect to depth -- particularly at several feet below the bed surface. Where channel degradation is anticipated, it is essential to determine the gradation of the material as a function of depth so that this information may be used in calculations for the armor layer.

Section 4.09. Standardization of Sampling Equipment, Techniques and Methods of Analysis

The Committee on Sedimentation of the Water Resources Council has responsibility for standardizing sediment sampling equipment and techniques in the United States. This need grew out of the great impact that sampling equipment and techniques have on the scatter of data. Even with standardization, it is necessary to record the type of equipment and analysis technique used for each sample.

Section 4.10. Permanent Sediment Ranges

Because of the uncertainty in present analytical techniques for handling sediment problems and to give insight into the prototype behavior of sediment problems, permanent sediment ranges are usually established along reservoirs and in channels where aggradation or degradation trends are expected. These ranges are permanently marked and resurveyed periodically to determine the amount of change in the cross section due to scour or deposition.

It is essential that sediment ranges be close together in places where the greatest amount of scour or deposition will occur. In the case of deposition in reservoirs, this would be in the upstream extremity of the reservoir where the inflowing water establishes the backwater curve. In the case of narrow reservoirs, ranges should be located at points of expansion. Ranges may be located further apart through that portion of the reservoir where deposits are not expected.

Immediately downstream from the dam, it is again desirable to locate ranges close together with the distance between them increasing with distance away from the dam. Control locations should be included if they are free to degrade. Sections should be resurveyed annually during the early life of a project. Later the time between resurveys can be extended perhaps up to five years, depending on how rapidly deposition or scour is occurring.

Sediment ranges alone do not provide useful data for calibrating analytical techniques such as the simulation model in Appendix VII. The gradation and amount of total inflowing sediment load, the inflowing water discharge, the water temperature, and the operating policy of the reservoir must also be known. Otherwise, the sediment range data will only be useful for monitoring the rate of deposition in the reservoir. This will not be a linear function with time; consequently, projections into the future will not be possible without an analytical technique.

CHAPTER 5. RESERVOIR SEDIMENTATION

Section 5.01. Nature of Reservoir Sedimentation Problems

The summary statement in Chapter 1 addressed deposition in reservoirs in terms of the conversion from kinetic and inertial energy to potential energy. This chapter on reservoir sedimentation identifies specific problem areas and methods of solution commensurate with the level of detail required at various stages between the early planning and final design of a reservoir project. Problem areas are associated with project purposes, as well as the physics of sediment movement, and the impact of changes in the bed elevation on the water surface profile. The following table correlates problems with project purposes in the order of increasing complexity of analysis.

The first six study objectives, "Project Feasibility" through "Aggradation of Tributary Channels" have been successfully accomplished using analytical techniques presented in this volume. The "Channelization for Navigation" requirement refers to constricting a river channel with dikes or revetments so that navigation depth is maintained by action of the flowing water rather than by dredging. Good first-approximations to the amount of constriction required have been made using techniques presented in this volume. However, final alignment of control structures (dikes and revetments) and identification of locations requiring over-contraction should be based on movable bed hydraulic model studies.

Table 5.01. Relationship Between Project Purpose and Sediment Problems

	Study Objective	Results Needed from Sediment Study
1.	Project feasibility	Total volume of deposits that will accumulate in the reservoir during the life of the project.
2.	Depletion of storage in single purpose reservoirs.	A total volume is satisfactory for conservation purposes but the vertical distribution is necessary for flood control reservoirs.
3.	Depletion of storage in multiple purpose reservoirs.	A vertical distribution showing storage depletion as a function of elevation.
4.	Reallocation of storage in completed projects.	Impact on the vertical distribution of sediment deposits as a function of elevation.
5.	Land acquisition/levee height design.	The change in average bed elevation at cross sections spaced along the reservoir.
6.	Aggradation of tributary channels.	The change in average bed elevation at cross sections spaced along each tributary.
7.	Channelization for navigation.	The amount of channel contraction required to maintain a specified bed elevation.
8.	Channel degradation and armoring downstream from the dam.	The amount of degradation and the distance it extends downstream from the project.
9.	Density currents through reservoirs.	Concentration of sediment material, elevation and thickness of the density current and sediment load passing the dam.
10.	Siting recreation, water supply or water disposal facilities.	Point values of bed elevation and water depth as related to general and local deposition (or scour).
11.	Navigation channel alignment and port facilities.	The shifting, back and forth across the stream, of point values of bed elevation.
12.	Shore erosion and beach stability.	Both a vertical and horizontal distribution of sediment movement including driving forces of the 3-dimensional reservoir current pattern, overland or local inflow, and action of the ground water table.

Two and three dimensional mathematical formulations of the hydrodynamic equations are presently being developed by several investigators, reference 4. In the future perhaps these will increase analytical capability for density current studies. Presently, these studies require hydraulic model testing.

The study objectives involved with siting facilities and locating navigation channels require hydraulic model analysis. Shore erosion and beach stability virtually require a prototype scale of testing.

Section 5.02. Data Requirements for Analyzing Deposition in Deep Reservoirs

The amount of data required to perform the various types of studies listed in table 5.01 increases with each item on the list. The first step is to estimate the total amount of sediment that will be available for deposition during the design life of the project. This requires the following data:

Table 5.02. Data for Total Deposition in a Reservoir

Type of Data	Source	Units
Design life of reservoir	Policy	Years
Reservoir capacity	Topographic maps	m^3 or ac. ft.
Water yield of watershed	Streamgage records, computations, or judgment	m^3/year or ac. ft/year
Sediment yield of watershed	Direct measurements, computations, or judgment	m^3/year or ac. ft/year
Composition of sediment material in terms of sand, silt and clay	Direct measurements	Percent
Unit weight of sediment deposits	Direct measurements or computations	lb./ft^3 or tons/m^3

With this level of information one can predict the volume of sediment deposits using trap efficiency techniques. This is an essential step in the early planning for a potential reservoir project.

Assuming flood control is a project purpose, the next level of detail in reservoir sedimentation studies is to divide the total volume of predicted deposits into that volume settling in the flood control pool and that volume settling in the remainder of the reservoir. Fig. 1.01 shows, conceptually, the deposition pattern to expect. This level of calculation requires the following, in addition to data listed above:

Table 5.03. Data for Calculating Deposition in Flood Control Pool

Type of Data	Source	Units
Depth of flood control pool	-	ft. or m
Depth of reservoir	-	ft. or m
Percent of time the water level in the reservoir is at or above the bottom of the flood control pool	Calculations	Percent

The next level of detail in reservoir sedimentation studies is to determine the location of sediment deposits in the reservoir so the new bed profile can be determined. This calculation addresses the land acquisition/levee height and channelization problems. In addition to data shown above, this calculation requires the following:

Table 5.04. Data for Distributing Sediment Deposits Along the Reservoir

Type of Data	Source	Units
Cross sections	Topographic maps	ft. or m
Operating rule for the reservoir elevation	Calculations	
Hydrograph for inflowing water discharge	Direct measurements or calculations	cfs or cms
Size of sediment particles entering the reservoir	Direct measurements	mm
Concentration of sediment in inflowing water	Direct measurements	mg/l
Water temperature	Direct measurement or judgment	°F or °C

Data requirements for hydraulic model studies are not presented in this volume.

The first three study objectives do not require a great deal of calculations and can easily be accomplished by manual methods. On the other hand, determining the location of sediment deposits requires voluminous amounts of calculations and those studies are best conducted with automatic data processing equipment.

Section 5.03. Calculation of Reservoir Deposition Using Trap Efficiency

The term "trap efficiency" is defined as

$$T_e = (Q_{si} - Q_{so})/Q_{si} \tag{5-01}$$

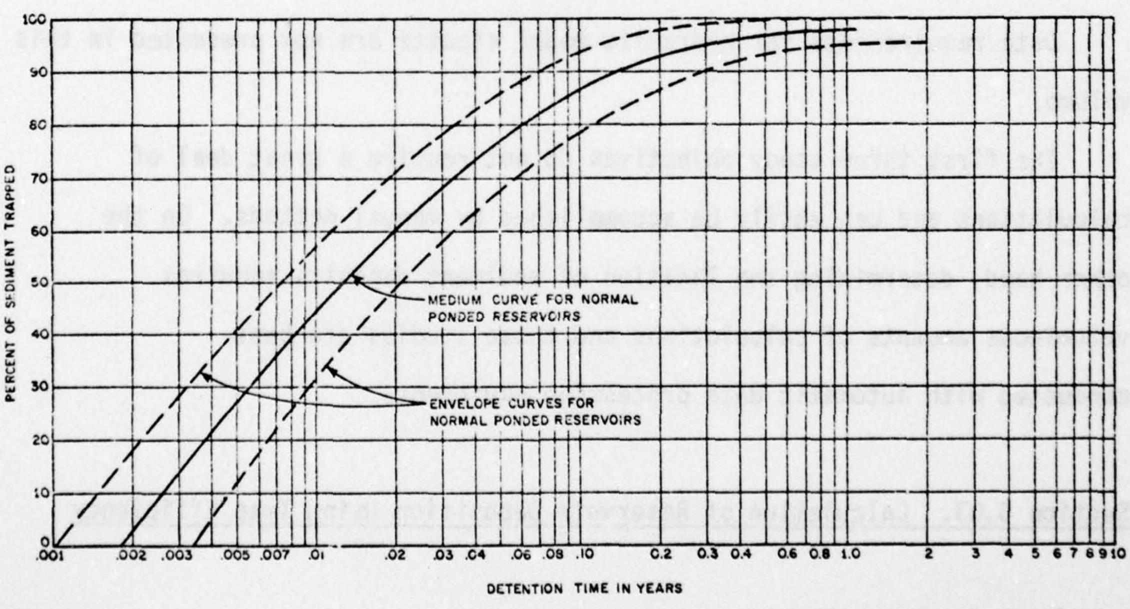
where

T_e = trap efficiency expressed as a decimal

Q_{si} = inflowing sediment load

Q_{so} = outflowing sediment load

Methods which utilize trap efficiency to calculate the volume of sediment deposits are sometimes referred to as detention-time methods. This name stems from correlations which demonstrate a relationship between trap efficiency and the time required for water to flow through the reservoir. One such relationship, developed by Gunnar Brune, (3), is shown in fig. 5.01.



NOTE: Reproduced from Gunnar Brune's Article, "Trap Efficiency of Reservoirs" Published in Trans. A.G.U., June 1953.

Fig. 5.01. Brune's Curve

In utilizing Brune's curve, flow through time is calculated as follows:

$$T_d = S/Y_w \tag{5-02}$$

where

S = Capacity of reservoir in ac. ft. or m^3

T_d = flow through time (or detention time) in years

Y_w = average annual water yield in units of volume/year

The following example, Lowsed Reservoir,1/ illustrates the calculation of total volume of sediment deposits using Brune's curve.

Given:

Design life of the reservoir (TIME)		=	100 years
Reservoir capacity, top of flood control pool (S)		=	3060 acre feet
Average annual water yield (Y)		=	36200 acre feet/year
Average annual sediment yield (Q_{si})		=	16000 tons/year
Composition of sediment material:	clay	=	25%
	silt	=	35%
	sand	=	40%
	total	=	100%

The unit dry weight for sediment deposits is not available for a proposed reservoir. Therefore, the values suggested in this volume, table 2.03, Unit Dry Weight for Sediment Deposits, are utilized along with equation 2-05 to calculate an average unit weight at the end of 100 years.

1/ This example was developed by Mr. Ernest L. Pemberton, United States Bureau of Reclamation, Denver, Colorado.

Table 5.05. Calculated Unit Dry Weight of Sediment Deposits

Sediment Material	γ_1 pcf	K	$\log_{10}(T)$	$\gamma_1 + K \cdot \log_{10}(T)$	% 100	γ_T pcf
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Clay	30	16	2	62	0.25	15.5
Silt	65	5.7	2	76	0.35	26.6
Sand	93	0	-	93	0.40	37.2
						79.3

It is convenient to convert sediment inflow from the average annual amount in tons/year to the total volume delivered during the 100-year period of analysis in acre feet.

$$V_d = Q_{si} \frac{\text{tons}}{\text{year}} \cdot \frac{1}{\gamma_{100}} \frac{\text{ft}^3}{\text{lb}} \cdot 2000 \frac{\text{lb}}{\text{ton}} \cdot \frac{1 \text{ ac. ft}}{43560 \text{ ft}^3} \cdot 100 \text{ years}$$

$$= \frac{Q_{si}}{\gamma_{100}} \cdot \frac{200000}{43560}$$

$$= \frac{16000}{79.3} \cdot \frac{200000}{43560}$$

$$V_d = 926 \text{ ac. ft.} \qquad (5\text{-}03)$$

The next step is the calculation of trap efficiency. Since this coefficient depends on the capacity of the reservoir and the capacity changes with time, it is customary to calculate a value for the beginning

and one for the end of the design life of the project. These calculations are shown below, starting with initial conditions.

$$T_d = S/Y_w$$
$$= 3060/36200$$
$$T_d = 0.084 \text{ years} \qquad (5\text{-}04)$$

Entering fig. 5.01 with a detention time of 0.084 years, the trap efficiency is read directly as 85 percent. The resulting amount of sediment deposition, may be calculated with the volume equivalent of equation 5.01.

$$Q_{si} - Q_{so} = T_e \cdot V_d$$

$$\text{Total Volume Deposited} = T_e \cdot V_d = 0.85 \cdot 926 \text{ ac. ft.}$$
$$= 787 \text{ ac. ft.} \qquad (5\text{-}05)$$

The final step is to refine these calculations by assuming the reservoir storage capacity is decreased by 787 acre feet and recalculating the trap efficiency following the same computation procedure as before. The result is 81 percent. Utilizing the beginning and ending trap efficiencies it follows that the average trap efficiency for the 100 year project life is 83 percent which results in 769 acre feet of sediment deposits in the reservoir.

Grain size does not enter directly into these calculations for trap efficiency, although it is apparent, intuitively, that the larger grain sizes would deposit first and only the smallest grain sizes would be transported through the reservoir. The impact of grain size, then, is inherent in the empirical data used to develop the trap efficiency curve. On the other hand, approximating detention time by utilizing

total reservoir capacity and annual water yield does not merit refinement of data to include particle size. Even so, the Brune's curves may be used to give a reasonable estimate of the total volume of sediment deposits to expect in a reservoir.

In making sedimentation studies for Dardanelle Reservoir on the Arkansas River, the U.S. Army Corps of Engineers District, Little Rock, Arkansas, USA, refined the trap efficiency calculations by establishing two trap efficiency curves. One of these curves was representative of the sand load and the other curve of the silt and clay load. The reservoir was subdivided into reaches and the storage in each reach determined so that for a given water discharge the detention time could be calculated for each reach and the sediment deposition could be calculated separately for sand, and silt and clay. The Little Rock District trap efficiency curve is presented in Appendix IV.

Section 5.04. Development of Trap Efficiency from Observed Data

The procedure which Little Rock District used in the development of their trap efficiency curve is contained in Appendix IV, entitled "Procedure for Development of LRD Trap Efficiency Curve."

Section 5.05. Calculation of Deposition in the Flood Control Pool

Fig. 5.02 shows an empirical relationship which can be used to determine how much of the total sediment deposition can be expected in the flood control pool (fig. 1.01). The "Flood Pool Index" is a measure

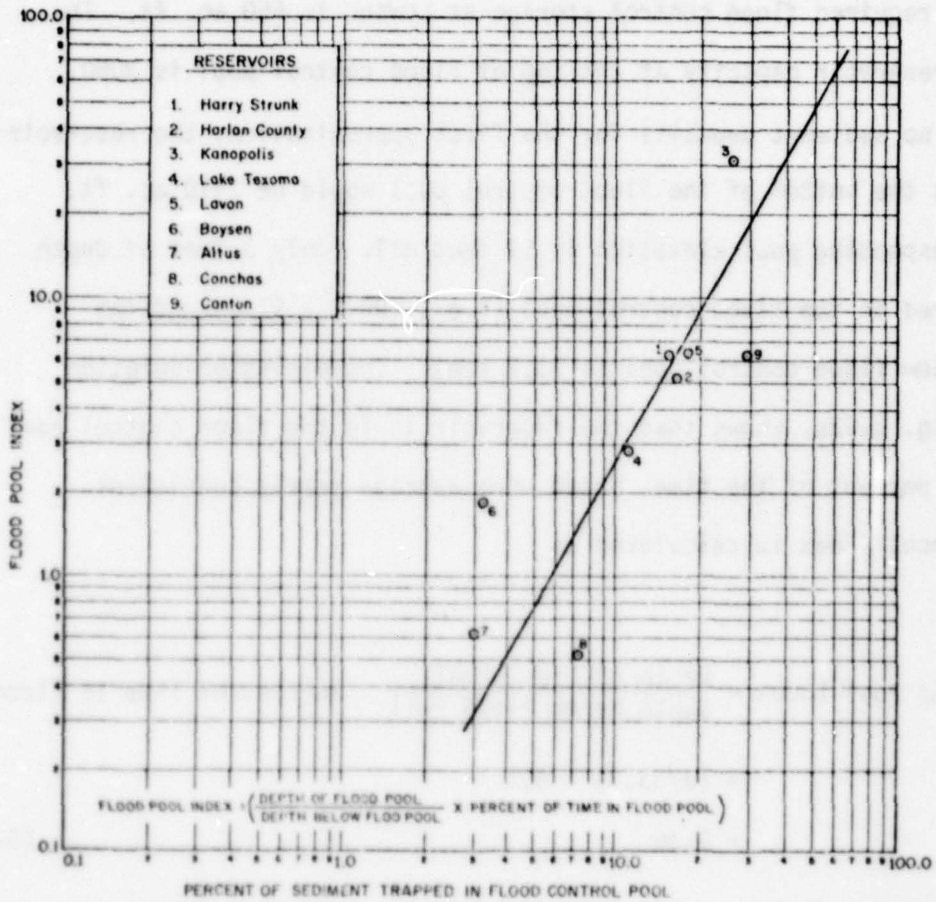


Fig. 5.02. Deposition in the Flood Control Pool

of the amount of time the reservoir remains in the flood pool and the relative depth of that pool. The index is defined by equation 5.06.

Necessary parameters for using this curve are listed in table 5.03, "Data for Calculating Deposition in Flood Control Pool." The calculations which require successive approximations, utilize the reservoir depth versus storage capacity curve as follows.

The required flood control storage at Lowsed is 650 ac. ft. The initial reservoir capacity at the top of flood control pool is 3060. Assuming no sediment deposits for the first approximation, the reservoir volume at the bottom of the flood control pool would be 2410 ac. ft. The corresponding pool elevation is 97 feet msl. Only 3 feet of depth is required in the flood control pool (i.e., 100.0 - 97.0) and the depth below flood control pool is 33.7 feet. The elevation-duration curve, fig. 5.03a, shows that the reservoir is in the flood control pool only 4.1 percent of the time, based upon average yearly conditions. A flood pool index is calculated as

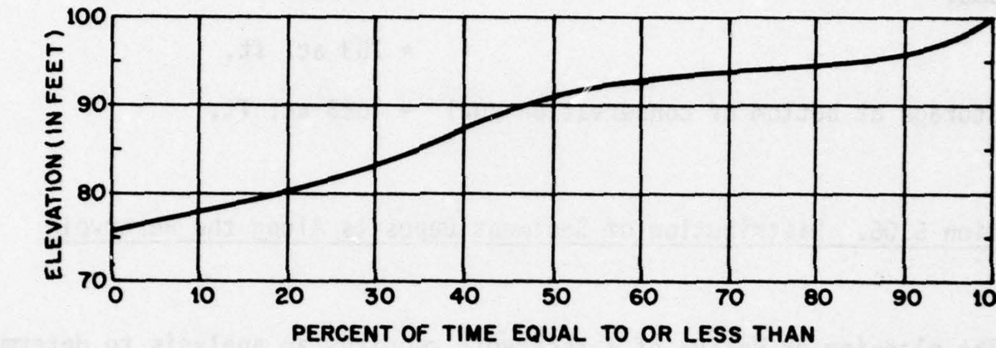
$$\text{Flood Pool Index} = \frac{\text{Depth of Flood Pool}}{\text{Depth Below Flood Pool}} \cdot \text{Percent of Time in Flood Pool}$$

$$= (3/33.7) \cdot 4.1$$

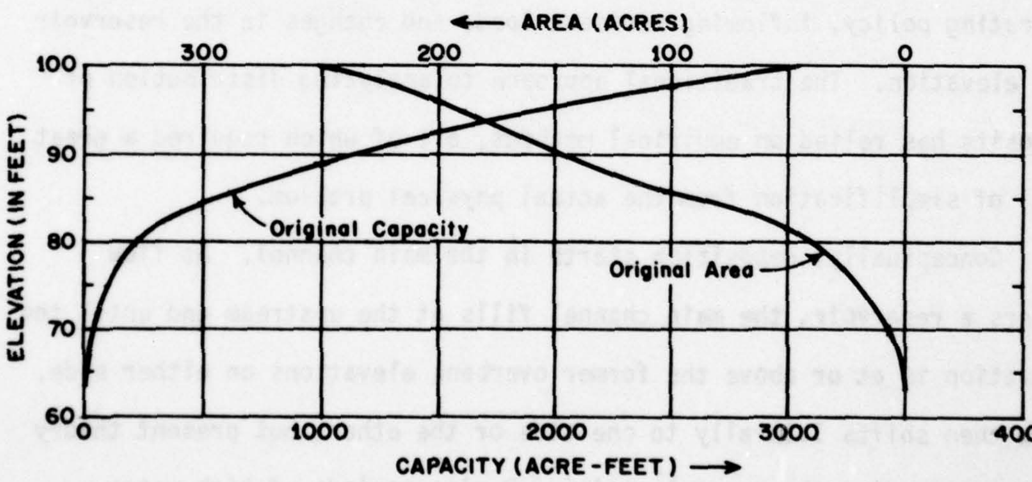
$$= 0.36 \qquad (5.06)$$

Entering fig. 5.02 with this index, the resulting amount of deposition in the flood control pool is read as 3 percent. The resulting 100 year volume is 3 percent of 787 ac. ft. which, rounded off, is 24 ac. ft. This additional storage for sediment does not change the flood pool depth on the second approximation and, therefore, it is adopted for planning purposes.

As a rough check, the available conservation storage at the end of 100 years may be determined as follows:



a. STAGE DURATION CURVE



b. AREA AND CAPACITY CURVES

Fig. 5.03. Duration and Capacity Curves for Lowsed Reservoir

Storage at top of conservation pool	= 3060 - (650 +24)
	= 2386 ac. ft.
Sediment deposition in conservation pool	= 787-24
	= 763 ac. ft.
Storage at bottom of conservation pool	= 1623 ac. ft.

Section 5.06. Distribution of Sediment Deposits Along the Reservoir

The planning or design of a reservoir requires an analysis to determine how sediment deposits will be distributed in the reservoir. This has been the most difficult aspect of reservoir sedimentation to deal with because of the complex interaction between hydraulics of flow, reservoir operating policy, inflowing sediment load, and changes in the reservoir bed elevation. The traditional approach to analyzing distribution of deposits has relied on empirical methods, all of which required a great deal of simplification from the actual physical problem.

Conceptually, deposition starts in the main channel. As flow enters a reservoir, the main channel fills at the upstream end until the elevation is at or above the former overbank elevations on either side. Flow then shifts laterally to one side or the other, but present theory does not predict the exact location. During periods of high water elevation, deposition will move upstream. As the reservoir is drawn down, a channel is cut into the delta deposits and subsequent deposition moves material farther into the reservoir. The lateral location of the channel may shift from year to year, but the hydraulic characteristics

of it will be similar to those of the natural channel existing prior to impounding the reservoir. Vegetation will cover the exposed delta deposits and thus attract additional deposition until the delta takes on characteristics of a flood plain.

The diameter (size) of sediment particles commonly transported by streams ranges over five log cycles. As flow enters a reservoir, coarser material deposits first and the finest material is carried well into the reservoir, even to the point of passing the dam. In order to calculate the volume of material which will deposit as a function of distance, grain size must be included as well as the magnitude of the water discharge and the operating policy of the reservoir.

Reservoir shape is an important factor in calculating the deposition profile. For example, flow entering a wide reservoir spreads out, thus reducing transport capacity, but the path of expanding flow does not necessarily follow the reservoir boundaries. It becomes a 2-dimensional problem to calculate the flow distribution across the reservoir in order to approximate transport capacity and therefore the resulting deposition pattern. On the other hand, flow entering a reservoir that is narrow has a more uniform distribution across the section resulting in hydraulic conditions that are better approximated by one dimensional hydraulic theory.

Flood waves attenuate upon entering a reservoir. Therefore, their sediment transport capacity decreases from two considerations: (1) a decrease in velocity due to the increase in flow area and (2) a decrease in velocity due to a decrease in water discharge (attenuation) resulting

from reservoir storage. As reservoir storage is depleted by the sediment deposits in the delta, the impact of attenuation on transport capacity diminishes. The resulting configuration, therefore, is assumed to depend upon the first consideration whereas the time for delta development is influenced somewhat by the second consideration.

A very useful technique for estimating the deposition of suspended sediment in deep reservoirs is presented in Appendix VI. This computer program does not actually change bed elevations; consequently the user should run two conditions before accepting the results: (1) initial bed elevation condition, and (2) calculated bed condition for end of reservoir life, determined from (1).

The Engineering Technical Letter, "Distribution of Reservoir Sediment Deposits," ETL 1110-2-64, dated 7 July 1969, Department of the Army, Office of the Chief of Engineers, Washington, DC 20314, by Mr. Brice L. Hobbs is included in Appendix V to give insight into reservoir sedimentation problems. In this ETL Mr. Hobbs points out several weaknesses in "present empirical methods" (1969) for distributing sediment deposits. These involve "total sediment loads," "average trap efficiencies," and "gross volumes of sediment trapped." The weaknesses have been overcome to a large extent by using analytical methods that can be applied with the aid of the electronic computer.

The final approach presented in this chapter is based on digital simulation, using the computer program "Scour and Deposition in Rivers and Reservoirs," described in Appendix VII. This approach eliminates the requirement of working with many of the averages and approximations

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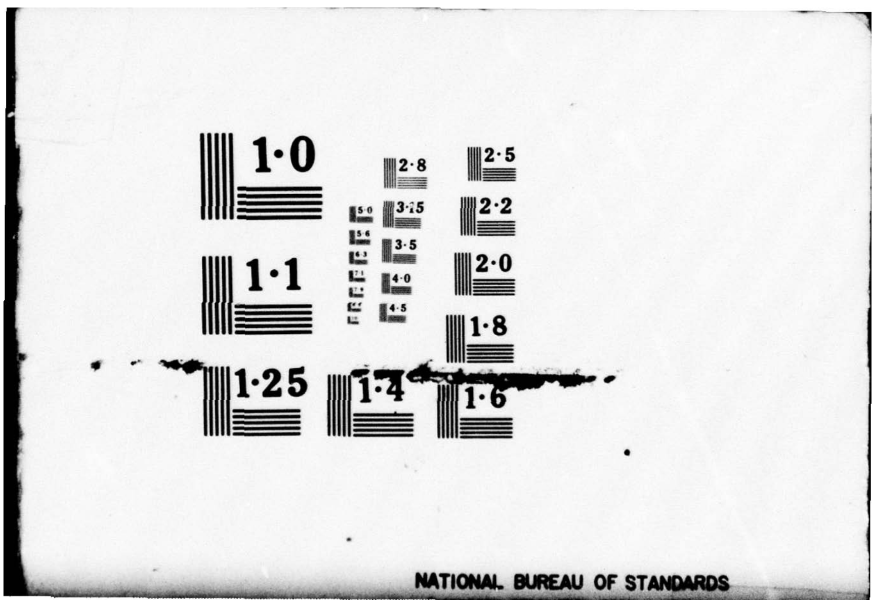
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of the reservoir behavior and increases the engineer's capability to approach sediment distribution problems from the standpoint of simulation, that is, from the standpoint of including a great deal of detail about reservoir operation, the inflowing sediment load, grain size of the material, the inflowing water discharge, hydrograph and reservoir shape, and changes in bed elevation with respect to time.

However, it is a one dimensional steady flow technique and does not attempt to locate the position of the channel through delta deposits. It does recognize, however, that ultimately the channel will exist and will be similar (in geometric size) to the natural channel that existed prior to impounding the reservoir. The results obtained enable prediction of an ultimate deposition profile through the delta deposits. Thus, the impact of deposition on the water surface profile and on the upstream limits of deposition can be determined.

Probably the most difficult problems involving the distribution of sediment deposits are associated with the flow through shallow reservoirs. Therefore, the example chosen to illustrate the aforementioned simulation techniques is a reservoir project which is sufficiently shallow so that during some inflow periods the deposits are actually entrained from the bed and moved further down into the reservoir.

The project is shown on fig. 5.04. This is a multipurpose project including hydroelectric power and navigation among other project purposes. The problem is complicated by the fact that levees are required for flood protection in the vicinity of the upstream

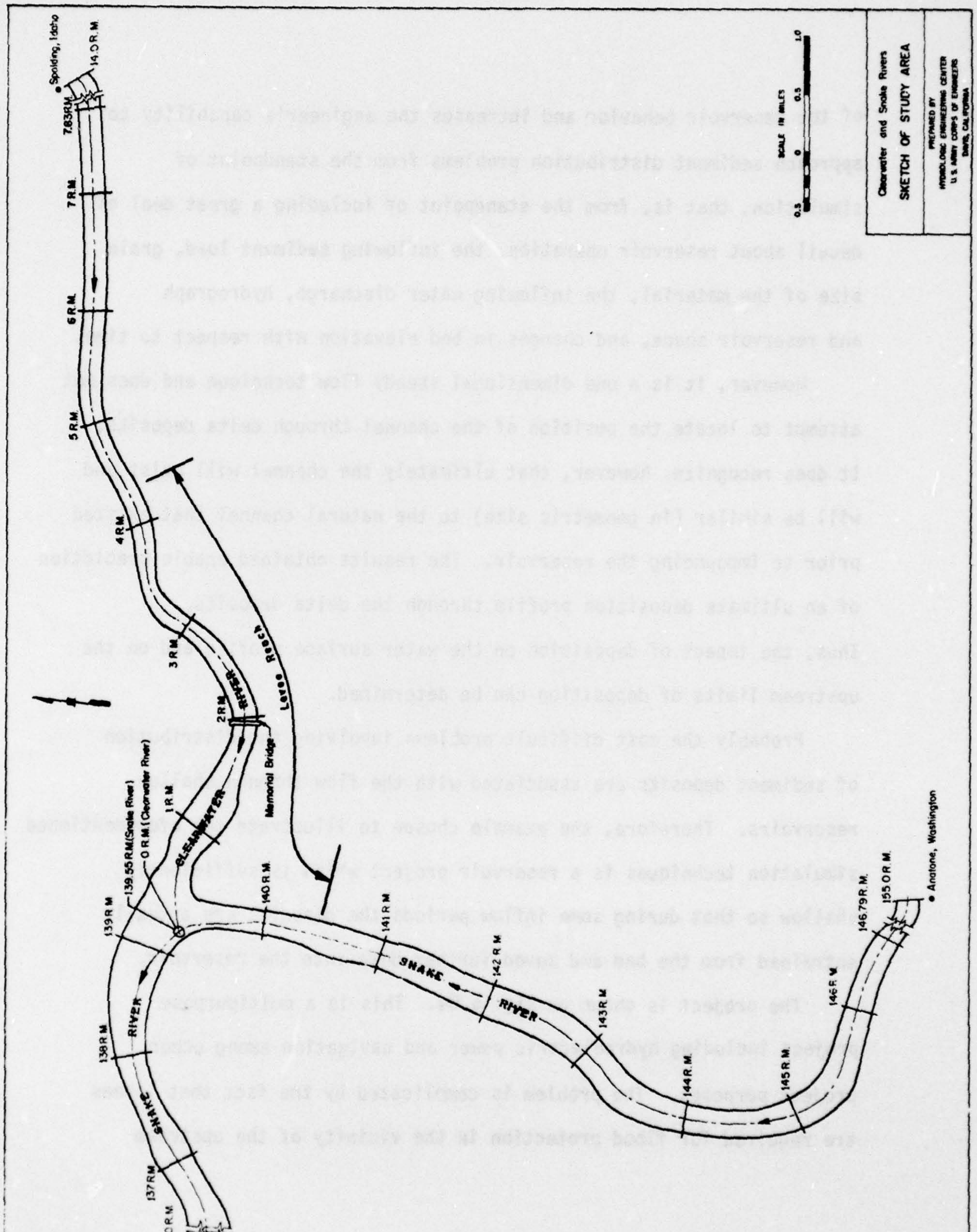


Fig. 5.04. Cross Section Locations, Lower Granite Reservoir, Sedimentation Study

Figure 1

limit of the reservoir project. Therefore, it is necessary to estimate the impact of future sediment deposits on levee heights.

Basically, the data required are cross sections and Manning n-values for use in backwater computations; the inflowing sediment load in tons per day as a function of the water discharge, the gradation of material in the stream bed; the operating rules at the dam, the water inflow hydrograph to the reservoir and the water temperature. Briefly, the sequence of events in the simulation study are as follows: The hydrograph of flows is converted to a histogram for which each discharge has an associated duration in days. The first discharge event is entered and a water surface profile calculated to determine the velocity, slope, depth and width at each cross section. The inflowing sediment load associated with that water discharge is entered at the upstream end and routed through the reservoir using the hydraulic parameters mentioned above. Deposition or scour is then calculated for each reach based on sediment inflow and outflow for that reach. Finally, the amount of change in the bed elevation is calculated for each cross section and cross section coordinates in the movable bed are changed. This completes the first pass through the calculations. A sample of the data involved is illustrated in the following figures and tables.

Fig. 5.05 shows a typical cross section with the limits of movable bed assigned. The user specifies the portion of the cross section over which deposition will occur.

Hydraulic roughness is assumed to be the same throughout the life of the project. This is a rather significant assumption since hydraulic

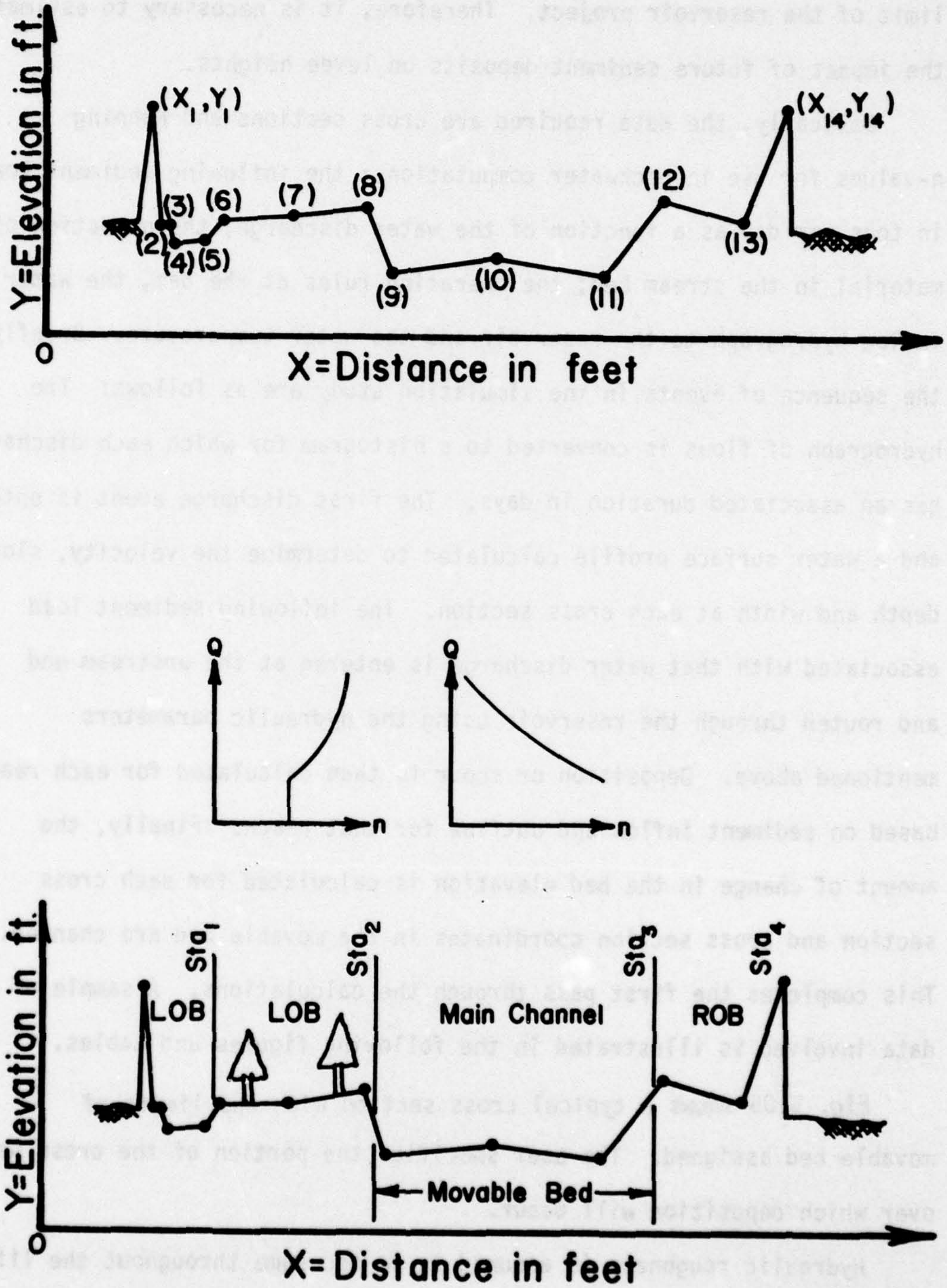


Fig. 5.05. Modeling Complex Cross Sections

roughness depends on both the grain size and bed form. The assumption is that, as the new equilibrium bed is approached, both grain size and bed form will return toward those existing in the natural state. One should evaluate the sensitivity of such an assumption by varying the n-value. Better hydraulic roughness theories, than are presently available are needed.

Table 5.06 shows the type and level of detail available for describing the inflowing sediment load. Both bed load and suspended load are considered. This table corresponds to a water discharge of 100,000 cfs. In the actual study similar information was developed for water discharges varying from 5000 to 200,000 cfs. Neither of the rivers entering the reservoir are high contributors of sediment. The Clearwater, for example, conveys only about 100 acre feet a year and the Snake produces only about 320 acre feet per year. Nevertheless, over the project life, both streams have the potential of depositing a sufficient depth of material to make a substantial impact on the water surface profile elevation for the levee design flood. Another point about the inflowing sediment load relates to the relative amounts of bed load and suspended load. Since the bed load comprises only about 2 percent of the total inflowing load, one is tempted to rely only on suspended load measurements and neglect the bed load altogether. However, for a water discharge of 100,000 cfs, calculations show that 90 percent of the gravel (bed load) deposits upstream from mile 2.6 and the sand does not deposit until the flow reaches about mile 2, fig. 5.06. This

Table 5.06. **Distribution of Sediment Load by Grain Size Class**

Clearwater River

Water Discharge, cfs 35,000

Total Bed Load, tons/day	130	(1)
Total Suspended Load, tons/day	1500	(1)
Total Sediment Load	1630	

Grain Size (1) Diameter mm	Classification	Percent of Total Bed Load ÷ 100 (2)	Bed Load tons/day	Percent of Total Suspended Load ÷ 100(3)	Suspended Load tons/day	Total Load Col. (4) + (6) tons/day
(1)	(2)	(3)	(4)	(5)	(6)	(7)
< .0625	silt & clay	.04	.05	.54	810	810
.0625 - .125	VFS	.10	.13	.10	150	150
.125 - .250	FS	2.75	4.0	.13	195	199
.250 - .500	MS	16.15	21.0	.19	285	306
.500 - 1.000	CS	13.28	17.0	.04	60	77
1.000 - 2.000	VCS	1.19	2.0			2
2 - 4	VFG	1.00	1.0			1
4 - 8	FG	1.41	2.0			2
8 - 16	MG	2.34	3.0			3
16 - 32	CG	6.33	8.0			8
32 - 64	VCG	23.38	30.0			30
> 64	cobbles & larger	32.03	42.0			42
Total		1.0	130.18	1.0	1500	1630

Note: (1) Values were read from the "Sediment Load" curve, 1972-74 measurements.
(2) These values were calculated by analyzing measured hydraulic parameters and measured bed loads using the computer program "Total River Sand Discharge and Detailed Distribution" by F. B. Toffaleti.
(3) These are representative values determined graphically by plotting the results of sieve analyses and developing a single, percent finer curve from all samples analyzed.

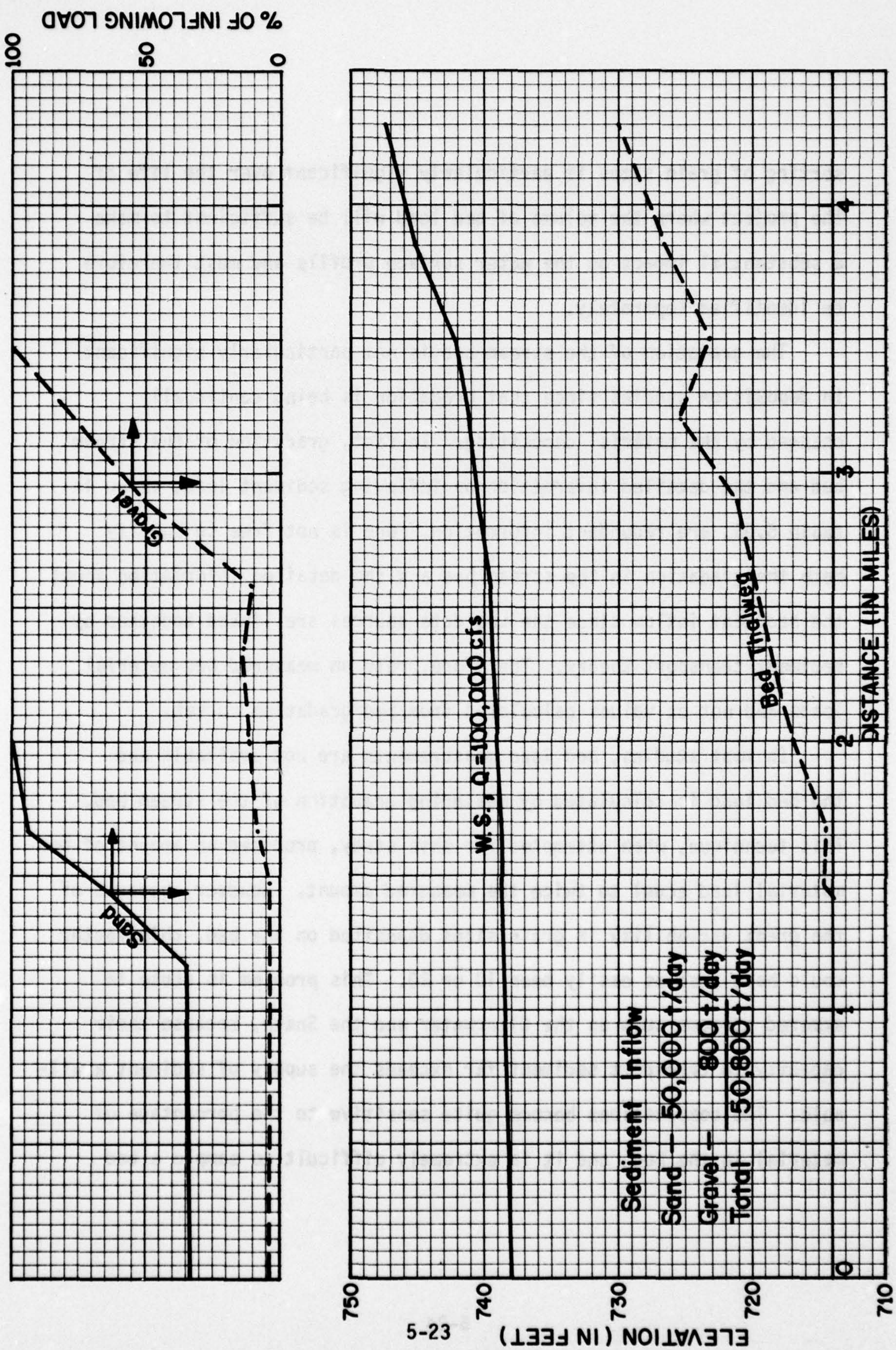


Fig. 5.06. Hydraulic Sorting as Flow Enters a Reservoir

sorting of grain sizes is particularly significant over the life of the project where the volume of bed load will be sufficient to make a substantial impact on the water surface profile and must therefore be identified separately.

The gradation of the stream bed is not particularly significant in deposition studies since that gradation is being continually changed by the material depositing. In fact, gradation of the stream bed and the detailed information on inflowing sediment load, shown in table 5.06, are redundant information. One is not free to specify both the gradation in the stream bed and the detailed information about the sediment inflow since the two data sources are linked together by sediment transport theory. Therefore, rely on measured bed material loads and not on values calculated from bed gradation curves.

In most studies, bed load measurements are not available and the bed load is calculated by measuring gradation of the stream bed. This technique, when attempted for this study, produced an amount of bed material load equal to twice the measured amount. However, because of the great variability in grain sizes deposited on the bed, this factor could have just as easily been 10 or 20. This problem is acute in armored streams such as the Clearwater and the Snake, because their capacity to transport sediment far exceeds the supply of sediment available. The computations become quite sensitive to the percentage of material in the bed, and it is extremely difficult to sample a bed

for which the grain size ranges from very fine sand to cobbles and larger and have any assurance that the sample is representative of the entire bed. Therefore, in initial problem areas such as this involving levees in an urban area, measure all the data presented in table 5.06.

The inflowing water discharge hydrograph was analyzed in periods varying from one day during the peak flood season up to monthly values during the period of low flow. A sample period is shown in fig. 5.07. Water temperature was obtained from records at a nearby stream gaging station and the operating policy of the reservoir was specified, in this case, to be a constant pool elevation 738 for the entire 50 years of water discharge hydrograph.

The results of the analysis are shown on fig. 5.08, Deposition in Lower Granite Reservoir. In addition to calculating the average bed profile and the resulting impact on the levee design flood profile, the simulation technique calculated the trap efficiency over the 50 year life of the project to be 30 percent. Also, the amount of maintenance dredging required to support navigation up to mile 2 was calculated. Other simulation runs were made to test the impact of the maintenance dredging on both the sediment deposits and the water surface profile.

Section 5.07. Impact of Natural Aggradation Trends

Using a simulation technique, such as the Scour and Deposition program in Appendix VII, to calculate the distribution of sediment deposits

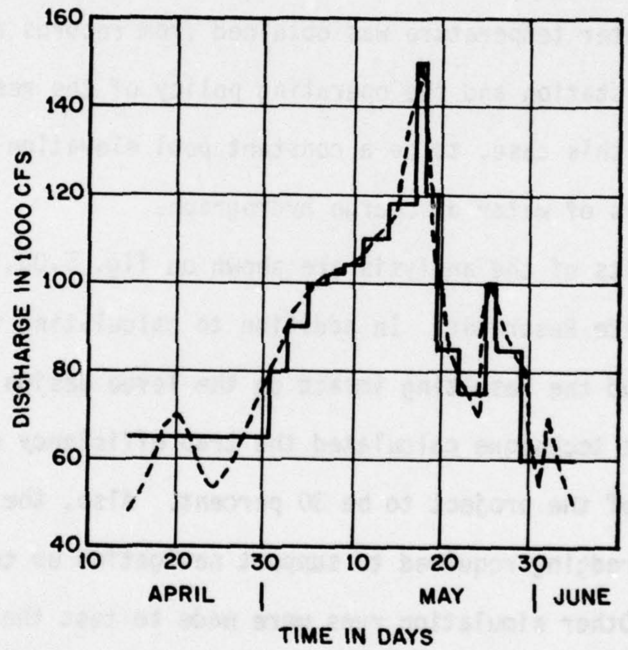


Fig. 5.07. Standard Project Flood

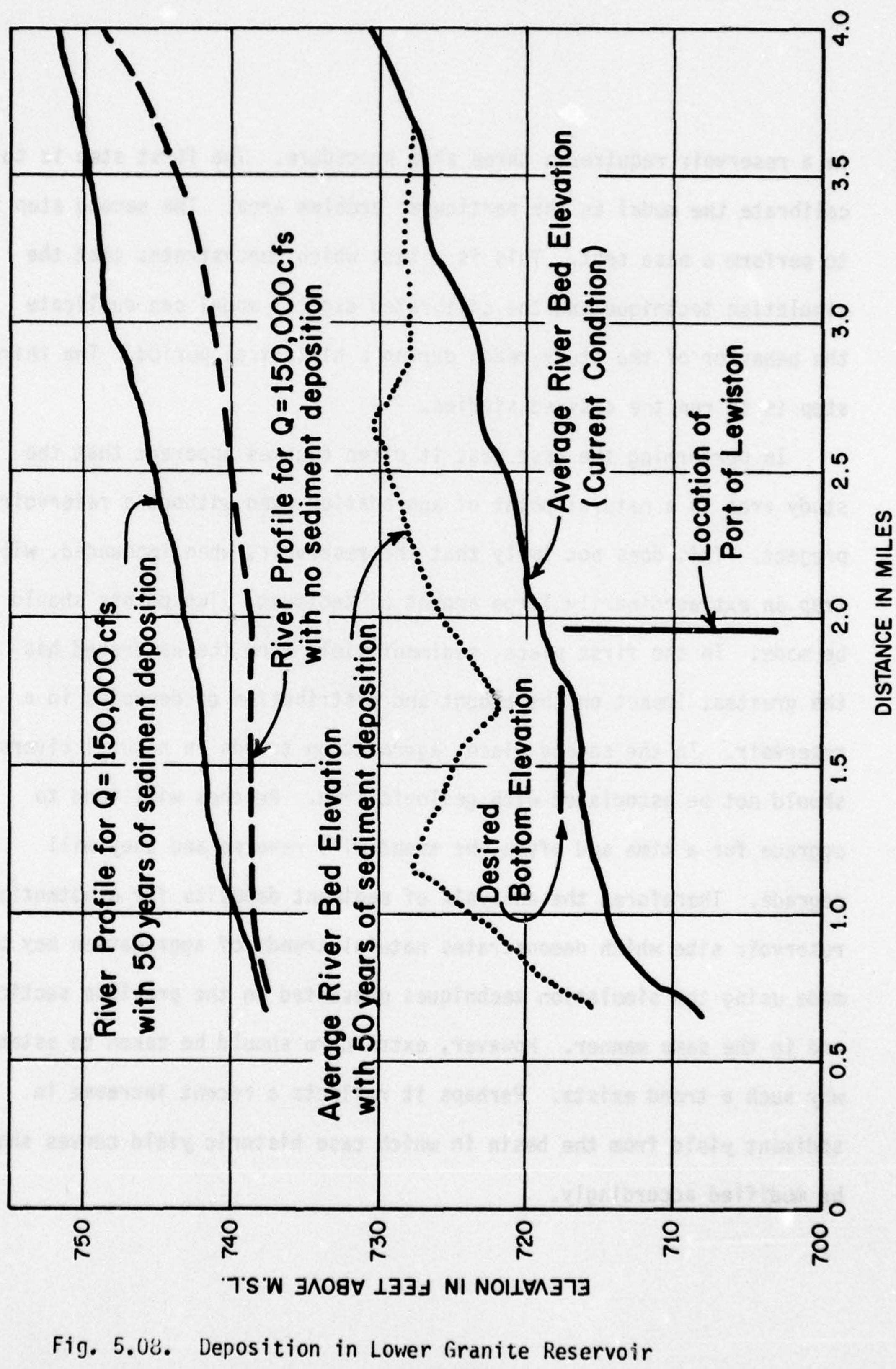


Fig. 5.08. Deposition in Lower Granite Reservoir

in a reservoir requires a three step procedure. The first step is to calibrate the model to the particular problem area. The second step is to perform a base test. This is a test which demonstrates that the simulation technique and the calibrated digital model can duplicate the behavior of the study reach during a historical period. The third step is to run the desired studies.

In performing the base test it often becomes apparent that the study area is a natural point of aggradation even without a reservoir project. This does not imply that the reservoir, when impounded, will trap an extraordinarily large amount of sediment. Two points should be made. In the first place, sediment yield from the watershed has the greatest impact on the amount and distribution of deposits in a reservoir. In the second place, aggradation trends in natural rivers should not be associated with geologic time. Reaches will tend to aggrade for a time and often the trend will reverse and they will degrade. Therefore, the analysis of sediment deposits for a potential reservoir site which demonstrates natural trends of aggradation may be made using the simulation techniques presented in the previous section and in the same manner. However, extra care should be taken to establish why such a trend exists. Perhaps it reflects a recent increase in sediment yield from the basin in which case historic yield curves should be modified accordingly.

Section 5.08. Impact of Upstream Reservoirs in the Basin

It is important to identify and locate any reservoirs in a basin where a sediment study is to be made. The projects upstream from the point of analysis potentially modify both the sediment yield and the water discharge duration curve. Both are very significant.

The date of impoundment is essential information. With this, one may coordinate observed inflowing sediment loads with whatever conditions existed in the basin during the periods selected for calibration and verification.

Useful information on the density of sediment deposits and the gradation of sediment deposits are often available from other reservoirs in the basin. Finally, other reservoirs offer a check on sediment yield.

Section 5.09. Erosion Control Measures

Erosion control measures refer to land use and farming practices in the basin. One is always a bit uncertain about how much credit to give erosion control measures when projecting sediment yield into the future. It is very likely that no credit should be given for the sand sizes and larger material. On the other hand, the silt and the clay sizes of material may undergo reduction by erosion control measures. Over the long run, it will be the management of those measures that insures they will continue to be effective.

Farming practices conducive to erosion control were implemented many years ago. Construction and industrial practices, on the other hand, are just now beginning to implement erosion control measures. Possible techniques are in the form of mulch, of seeding disturbed land surfaces, of stabilizing the soil with chemicals and of utilizing terraces and sediment traps to prevent material from entering the natural stream system. Any one construction project is going to be short lived compared to the life of a water resource project. However, many areas undergo continual construction activity and one cannot ignore the impact this has on sediment washing into the natural stream system. Potential increases of 50 to 100 times natural erosion rates can be associated with construction activities.

Section 5.10. Land Use Changes in the Basin

Land use can impact directly on sediment yield from the basin. For example, land being converted from pasture or forested area to row crop area can generate 10 to 20 times more sediment runoff. In most sediment studies it is customary to project existing land uses through the life of the project. That is, unless some explicit alternative future is being considered, the sediment yield from the watershed is considered to remain constant over the life of the project. A recent example where land use impacted substantially on sediment yield occurred when forested land was converted to strip mining. Because of

the close proximity to the main channel, the impact of this land use change was manifest immediately by an increase in the sediment being deposited in a local reservoir.

Section 5.11. Reservoir Sedimentation Ranges for Post Project Surveys

Cross sections should be located as for water surface profile calculations. These define points of contraction and expansion and points where bed change is expected or is existing. Many, but not necessarily all, of the same points would be valuable for use in monitoring the rate of sediment deposition in the reservoir. Permanent ranges, called sediment ranges, are usually established for this purpose. It is essential that these ranges be periodically surveyed at the same location. Therefore, permanent range markers should be installed to insure the range can always be located. It is always feasible to discontinue ranges that prove to be non-descriptive, but beware of the tendency to establish too few. Simulation studies provide useful guidance in establishing sediment ranges.

The frequency of which reservoir ranges are resurveyed depends on how much sediment deposition is occurring. In the initial operation of a project, annual resurveys are essential. Later on, as the reservoir delta develops, the change in delta elevation from one year to the next is not substantial and five or perhaps even more years may lapse between resurveys.

The volume of sediment deposits is readily determined by analyzing successive surveys of the sediment ranges. However, it is essential to know the inflowing water discharge, temperature, the inflowing sediment load, gradation of material in the inflowing sediment load and in the deposits, and the operating levels of the reservoir in order to utilize data collected from sediment range surveys to verify or improve analytical techniques. This is an important step in a project and one which is usually omitted because study funds are not available once the project goes into operation. Those responsible for the operation and maintenance of projects are urged to establish a procedure by which the testing of analytical techniques can be accomplished as data becomes available during the life of the project.

Section 5.12. Channel Behavior Downstream from the Dam

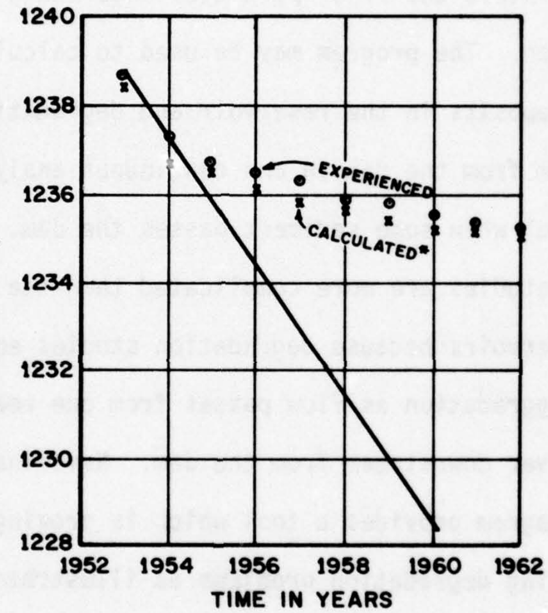
Degradation lowers the stream bed and, consequently, the tailwater rating curve at the dam. This is important from the standpoint of the dam foundation in the case of structures built on piling, and also with regard to impact on stilling basin performance. An important aspect of degradation studies is to locate the extent of degradation downstream from the dam. Rock outcrops or other hard bottom controls may reduce the vertical amount of degradation, but not the distance over which degradation problems exist. This distance is controlled by the modified flow duration curve and availability of bed material to replenish material removed by the reservoir.

The computer program, "Scour and Deposition in Rivers and Reservoirs," develops the armor layer by the selective removal of the finer grain sizes from the bed. Coarser sizes are removed at a much slower rate according to transport equations, and as a result the coarser sizes collect on the stream bed as degradation continues. The coarse particles shield the finer particles underneath and reduce the rate of degradation. The program may be used to calculate both the distribution of deposits in the reservoir and degradation of the channel downstream from the dam in one continuous analysis. This is particularly useful when some sediment passes the dam.

Degradation studies are more complicated than the calculation of deposition in reservoirs because degradation studies encompass both degradation and aggradation as flow passes from one reach to another in the natural river downstream from the dam. Nevertheless, the scour and deposition program provides a tool which is proving to be very useful for analyzing degradation problems as illustrated in fig. 5.09.

The degradation anticipated downstream from Ft. Randall Dam was arrested by armoring of the bed surface. The size of sediment in the armor layer composed less than five percent of the coarsest material sampled in the natural stream bed. Once established, flow regulation prevented the armor from being disturbed.

A rock outcrop or another reservoir is often suggested as a location for establishing the downstream end of a degradation study area.



* USING THE COMPUTER PROGRAM, " SCOUR AND DEPOSITION IN RIVERS AND RESERVOIRS."

NOTE: BASIC INFORMATION FROM U.S. DEPARTMENT OF AGRICULTURE, PROCEEDINGS OF THE FEDERAL INTER-AGENCY SEDIMENTATION CONFERENCE, MISCELLANEOUS PUBLICATION NO. 970, 1965.

Fig. 5.09. Degradation Downstream From Ft. Randall Dam

Certainly a reservoir is appropriate. However, a rock outcrop only limits the magnitude of degradation upstream from it and not the downstream migration of the degradation process. Two points are worthy of consideration relative to degradation studies.

The first is concerned with magnitude. A rock control does not stabilize the upstream bed at the elevation of the control. Bed material will be scoured upstream from the control until flow energy is in balance with resistance of the remaining bed material.

The second point concerns migration of channel degradation past the rock control. If other structures, such as bridge piers, water intakes, or diffusers, or if tributaries are present along the stream, the downstream extent of the degradation study area should include these. A sufficiently long reach should be established to include the transition from degradation to aggradation commonly observed downstream from existing projects.

It is possible that no degradation will occur. In fact, a reduction in channel capacity has been observed in numerous cases. This implies aggradation is occurring, and probably to narrow the channel in response to the modified flow duration curve. In other cases, the modified peak discharges lose transport capacity at major tributary junctions causing aggradation.

CHAPTER 6. AGGRADATION AND DEGRADATION IN FREE FLOWING STREAMS

Section 6.01. Introduction

The terms aggradation and degradation generally refer to trends in behavior of the stream bed profile. An aggrading stream is one on which the bed profile is tending to become steeper, whereas a degrading stream is one for which the bed profile is tending to become flatter.

Streams aggrade or degrade in discrete reaches. The process alternates between aggradation and degradation as the flow passes from one reach to the next. The fact that a reach of a river scours during the passing of a flood event does not make that a degrading reach. A degrading reach is one which projects a net lowering of the bed elevations with respect to time or, perhaps, a net widening of the river channel with respect to time. The rate at which aggradation proceeds depends on sediment yield, water yield, and grain size of sediment particles.

These discrete reaches are not fixed in space. They tend to shift back and forth with respect to time, with respect to the magnitude of water discharge and with respect to land use changes. Land use changes are importamt because they generally impact on sediment production from the basin. Other changes which are equally important are the construction of reservoir projects in the basin and modification of the water discharge duration curve (by interbasin transfer of flow or reservoirs).

Interbasin transfer of water is usually associated with large scale projects. However, this same concept is applicable, and the consequences more obvious, on small scale projects such as the construction of subdivisions, or other urban developments. Natural runoff patterns are altered, flow is collected into drains and other conveyances and degradation problems occur when these flows return to minor, natural conveyance channels.

In terms of Chapters 1 and 3 of this volume, the flow duration curve has been altered from that naturally forming the conveyance channel.

Section 6.02. Degrading Reaches

The obvious explanation as to why a reach degrades is that the inflowing sediment load is too small for the transport potential of the stream through this reach. The reach is providing a sediment supply for downstream points. Intensive meander is generally not associated with a degrading reach but rather the tendency is for the stream to become incised and perhaps to develop cutoffs.

The magnitude of degradation is arrested by several mechanisms. A rock outcrop or sill across the stream will tend to stabilize the bed. The development of an armor layer has the same effect. Oftentimes, the hydraulic conditions downstream from the degrading reach will change due to a downstream aggradation condition and this influence extends upstream. The classical examples of degrading reaches occur downstream from dams.

The stability of sediment material is often associated with tractive forces in accordance with the following figure. Tractive force is defined as

$$T = \gamma DS \tag{6-01}$$

where

D = water depth

S = energy slope

γ = unit weight of water

It should be pointed out that degradation is a function not only of the stability of material on the stream bed, but also the amount of the inflowing sediment load. A stream bed can be in equilibrium because material is being deposited as rapidly as it is being removed. The tractive force concept does not identify this type of equilibrium condition.

Section 6.03. Aggrading Reaches

The problem causing aggradation is just the opposite of that causing degradation. Reaches aggrade because the inflowing sediment load is greater than can be transported out of the reach by the hydraulics of flow. A tendency to meander is oftentimes associated with an aggrading reach, especially in streams having fine sediment with a non-cohesive bed and banks. Flow passing through an aggrading reach causes hydraulic sorting of grain sizes. Therefore, there is always

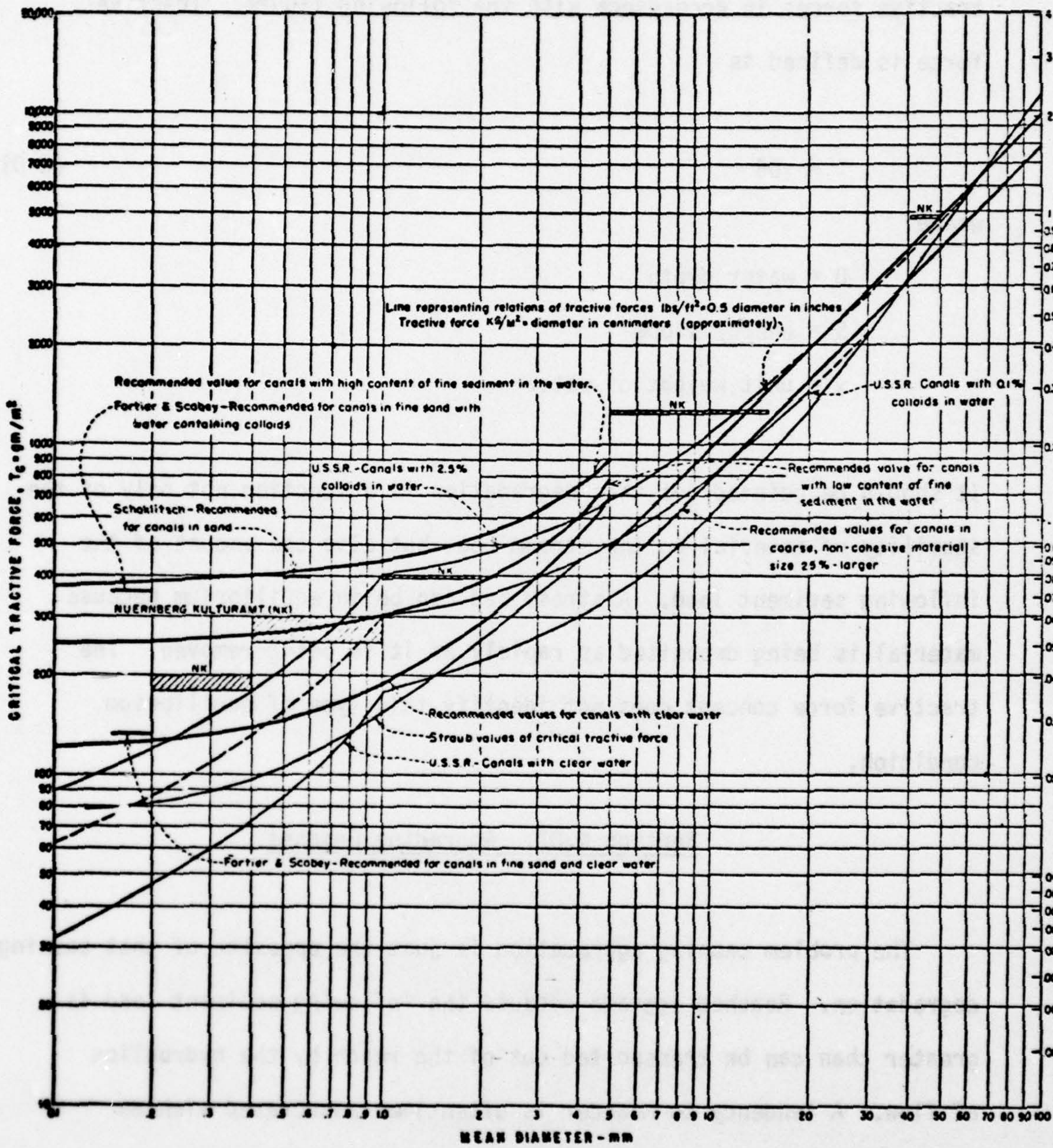


Fig. 6.01. LIMITING TRACTIVE FORCES RECOMMENDED FOR CANALS AND OBSERVED IN RIVERS

a deficiency of the coarser sizes as flow leaves the downstream end of the reach. The aggrading reach provides a temporary stopping place for sediment material moving downstream.

Aggradation is arrested by reducing the inflowing sediment load, by sorting to produce smaller particle sizes in the water-sediment mixture and by shifting in the downstream control due to a degrading condition at a downstream point.

Section 6.04. Shifts in the Stage-Discharge Rating Curve

Trends in the stage-discharge curve are good indicators of reach behavior. In alluvial streams, these curves typically exhibit a wide scatter of data which should not be construed as sample error. The range in scatter, between high and low data, is more appropriately attributed to aggradation, degradation, changing bed forms in the stream channel, or sediment transport rates produced by water temperature variances. The growth of natural levees will increase the discharge at which overbanks become effective. These factors should be considered in utilizing the stage discharge rating curves in the design of engineering projects, such as levees. It is not appropriate to develop an average line of best fit through the data, but rather an upper envelope curve is more appropriate for use in calculating the height of levees. Navigation depth and rip rap design, on the other hand, should utilize a lower envelope curve through the scatter of points. If the analysis of curves developed from successive years of stage-discharge data demonstrates a trend, then subsequent design studies must project the impact of this trend on project design.

Periodic measuring of profiles across the river will identify trends in lowering of the bed or enlargement of the channel. A meander does not represent an enlargement of the channel since both banks are shifting in the same direction. An enlargement of the channel would be represented when the two banks shift farther apart.

Section 6.05. Analysis of Aggradation and Degradation

The method for analyzing aggradation and degradation presented in Appendix VII of this volume is a movable bed, digital model. It can be compared with a fixed bed digital model as shown in figs. 6.02 and 6.03. Relative to fig. 6.02, if the topography of the river valley is known and the hydraulic roughness is known, the engineer may specify a water discharge and starting elevation, and he may then calculate the water surface profile. It is a direct calculation; there is no feedback such as that shown in fig. 6.03 by the double arrows. In fig. 6.03, sediment load has been added, and additional information on hydraulic roughness results. There is a great deal of uncertainty about how to predict the change in bed form and resulting impact on n-values, but it is at this point that the computer program presented in Appendix VII breaks into the loop for movable bed calculations. Basically, in utilizing that program, the assumption is made that n-values are either constant or they vary in the vertical with water discharge. The basic assumption, then, is that bed form can be related to water discharge.

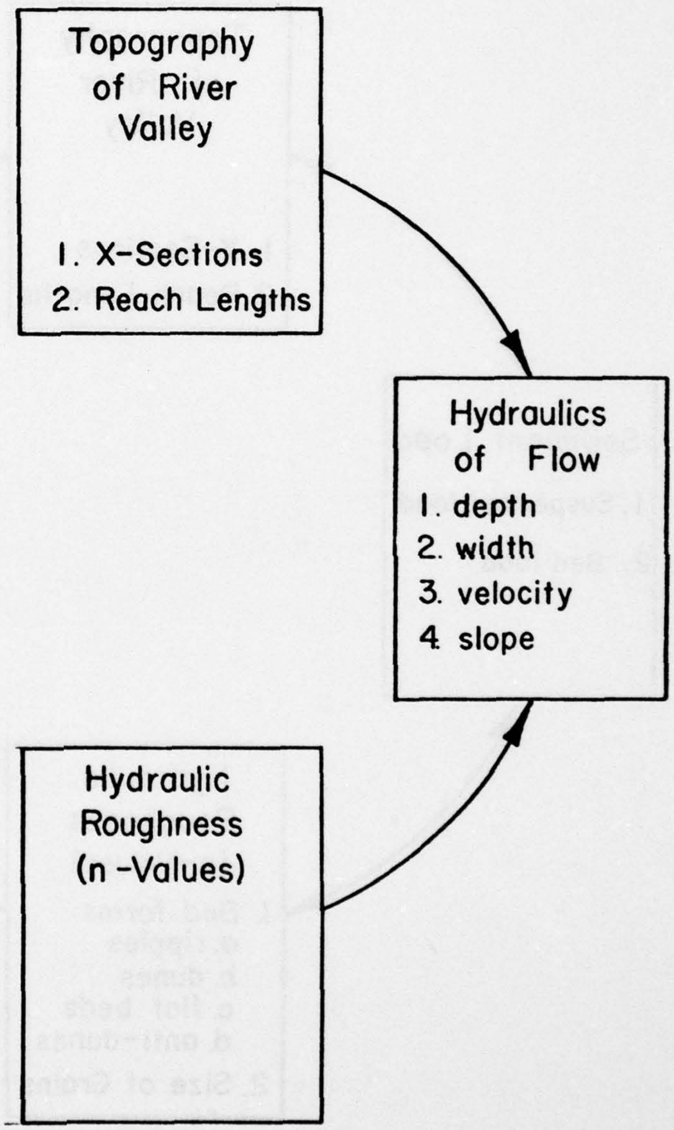


Fig. 6.02. FIXED BED MODEL

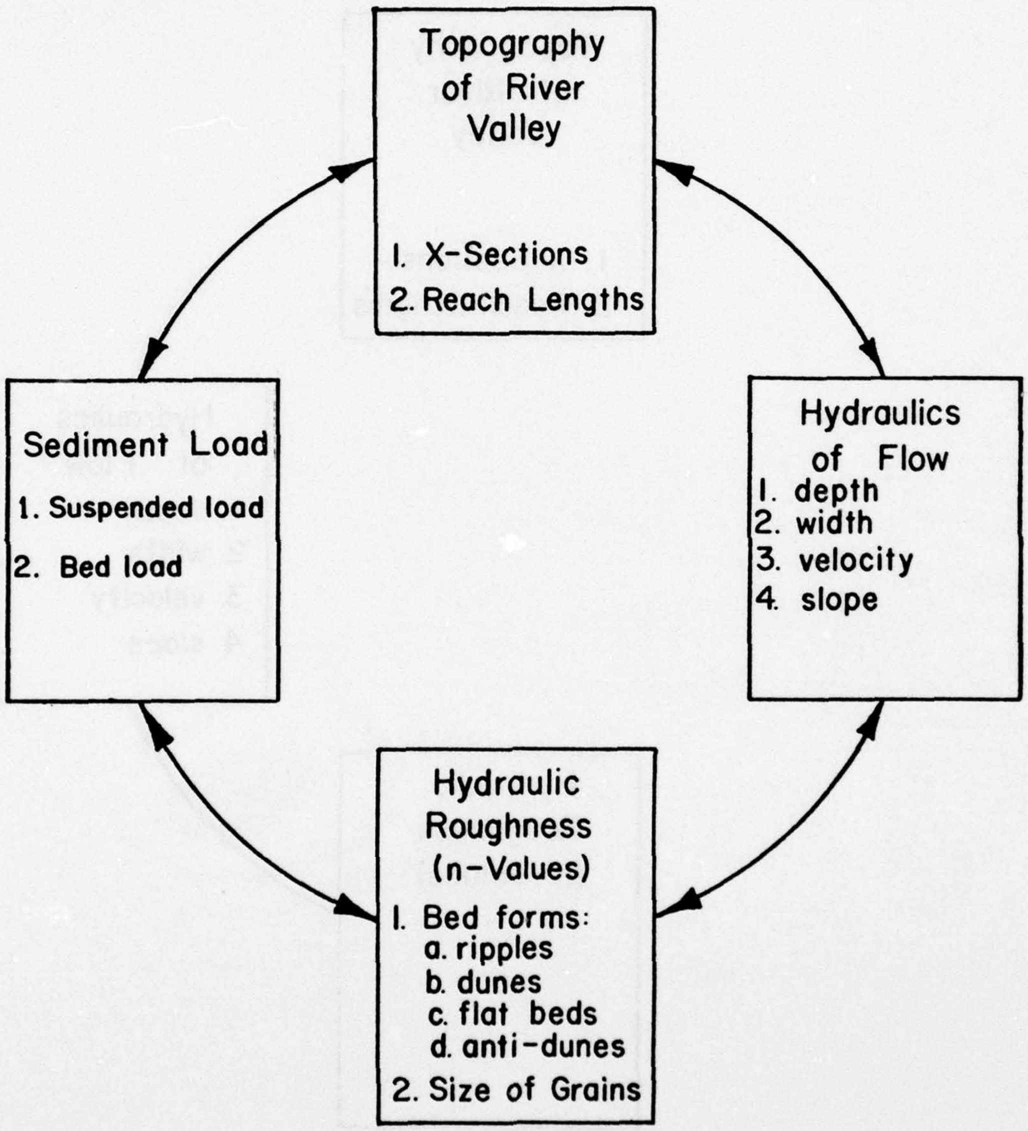


Fig. 6.03. MOVABLE BED MODEL

In proceeding with the analysis of aggradation or degradation, it is essential to follow the same guidelines given in Chapter 5.

1. Calibrate to an observed field condition
2. Verify that the calibrated digital model will reproduce the behavior of the river during a period of time, and
3. Analyze the degradation problem at hand.

Analysis of mobile boundary problems in free flowing streams adds a great deal of complexity to sedimentation studies. Input data is essentially the same as required for reservoir deposition studies; however, having the capability for aggrading and/or degrading complicates the calibration and base testing phase of studies. In summary, the required input data are as follows:

Initial channel geometry including a detailed description of natural levees along the channel

Water discharge hydrograph

Inflowing sediment load curve

Gradation of material in the stream bed

Water temperature

Sediment transport formula

a. Calibration of the Simulation Model

It is essential to calibrate the water surface profile calculations just as for a fixed bed study. The techniques are the same. A range of discharges varying from a low, in channel, discharge to the peak flood of interest should be analyzed to calibrate the n-values as the first step.

In fixed bed studies, one does not have to concern himself with the distribution of flow between the channel and the overbanks as long as the distribution is reasonable. In movable bed studies, it is a portion of the flow which travels in the channel that transports the bed material. For this reason, it is essential that the correct distribution of flow be known. Two parameters that may be evaluated are (1) cross section shape itself, especially the elevation at which water spills onto the flood plains and (2) the distribution of n-values between channel and overbank. This n-value information is seldom ever known; therefore, it becomes a matter of judgment to select the proper n-value for channel and for overbanks.

The third major item in the calibration is to determine and calibrate the inflowing sediment load. The amount and also the distribution with respect to grain size must be determined. The final type of data requiring calibration is the gradation of material in the stream bed.

The magnitude of water discharge selected for use during calibration is very important. If the flow is too low, the simulation model simulates a low water bed which often will have aggradation and degradation trends that do not appear to match the behavior measured in the prototype cross sections. If the water discharge is too large, aggradation and degradation trends may shift from those observed in the low water bed, but again they may persist in a manner that does not follow the overall behavior of the prototype. In order to simulate the behavior of the prototype over a period of time, one might consider using the dominant discharge as presented in Section 3.06.

It will be necessary to evaluate the water surface profile computations for discharges both higher and lower than this dominant discharge. However, primary emphasis may be placed on the dominant discharge to calibrate the inflowing sediment load, distribution by grain size in the inflowing load and the representative gradation of the bed surface itself.

The dominant discharge transports considerably more sediment material than the average daily volume, and therefore it is necessary to ratio the time scale to simulate the correct volume of sediment material moving during a year. This is quite straightforward once the total sediment yield and the sediment load associated with the dominant water discharge are known. It should be pointed out that sediment volume calculations are related to the total sediment load carried by the dominant discharge and not just the bed load when calculating a time scale.

By definition of dominant discharge one expects the calculated behavior of the river channel to follow the same trends as observed in the prototype. If this is not the case, one must re-evaluate analytical model calibration for n-values, the amount of material in the inflowing sediment load, the distribution by grain size of material in the inflowing sediment load, and the gradation of material in the stream bed.

These calculations assume the flow is distributed properly between the channel and overbanks. The dominant discharge itself is an inbanks flow. It will be a rather high flow, approximating that of bank full, oftentimes. Specifying cross section geometry such that natural levees

are simulated is critical in this calibration study. If at one point or another the water discharge does flow into the overbanks, the correct distribution of n-values between the channel and the overbanks is essential. A representative geometry and the proper distribution of n-values must be developed before problems with sediment transport may be resolved.

The following performance criteria is suggested for use in determining when a model is properly calibrated. For a discharge equal to the dominant discharge, trends in stream bed elevation should approximate the behavior of the prototype. That is, degradation trends in the analytical model should correspond in magnitude and location to those in the prototype and, likewise, aggradation trends in the model should correspond in magnitude and location to those in the prototype. The sediment load moving from point to point in the model may vary a great deal. However, at points corresponding to gage locations, the sediment load passing should match that observed in the prototype. Once the model is calibrated for the dominant discharge, it is necessary to test performance at a high discharge and at a low discharge. One can only check n-values and distribution of flow since, for any single discharge other than the dominant discharge, the model will not necessarily respond to the trends observed in the prototype. Calibration is completed with this phase of testing.

b. Base Test

The next step in problem analysis is to verify that the calibrated model will reproduce behavioral trends observed in the prototype. This

implies knowing a starting condition, calculating over a period of time, and comparing the results of the calculations with an ending condition in the prototype. Often, there are not enough data to identify a starting and an ending condition. In these cases, complete model verification is not possible. There are oftentimes trends that one can observe. For example, the magnitude of any scour or deposition should approximate that observed in the prototype and the calculated gradation of the bed surface should match that observed in the prototype.

The process of making small adjustments in the model data in order to achieve verification is often called fine tuning. It is in this phase of problem analysis that the engineer's understanding of river morphology is most essential. Any of the variables in the input data are susceptible to manipulation to some degree or another. However, adopted values must be reasonable and within the range of normal engineering experience. After the engineer has verified that the model can reproduce observed events, the study is ready to proceed to the third and final phase.

c. Production Run

It is most important that results from problem analysis be compared with the base test results established in the verification runs. This comparison will usually give a better response than absolute magnitudes of values calculated in the production run. The value of simulation is that any of the input data can be modified and the impact measured directly on either stream bed aggradation and degradation or the water surface profile elevations.

Section 6.06. Sediment Movement in Urban Conveyance Systems

Typically, urban conveyance systems for storm water runoff consist of storm drains in pipes interconnected with open channels. On the fringes of urban areas it is not unusual for flow to be collected into a well designed conveyance system in a subdivision only to pass out into a natural channel of limited capacity which becomes taxed with having to transport considerably more water than before the subdivision was constructed. Erosion of the natural channel is accelerated. These small conveyance channels obey the same regime concepts as those discussed earlier for larger rivers.

Deposition in the urban conveyance system itself is a common occurrence. Typical criteria for designing conveyance systems specify that velocities and/or bed shear stresses will be sufficiently high to prevent material from depositing in the section. Tractive force is a typical design criteria. As discussed in paragraph 6.02, tractive force alone is not sufficient to determine if sediment will deposit. Tractive force is a parameter for determining transport capacity; whereas deposition depends on both the transport capacity and the sediment yield from the basin.

Because of the large amount of construction activity in urban areas, there is always an abundance of sediment material available for washoff. When the rate of washoff exceeds the transport capacity of the conveyance system, deposition results, and the conveyance system takes on the characteristics of an alluvial stream in which the bed slope is in balance with sediment material in motion. Appropriate construction practices, including mulching, seeding, terracing, chemical applications and detention storage ponds, will help to reduce the deposition problem.

The analysis of sediment problems in urban drainage conveyance systems follows the same procedures discussed earlier for aggradation and degradation of free-flowing streams. Again, the two primary components of the problem are the determination of sediment yield and the calculation of sediment transport in the conveyance system. The sediment yield calculations are more complex than those for a major river because the conveyance system is much closer to the source of erosion and therefore the spatial distribution of sediment becomes an important consideration. Transport, on the other hand, follows the same physical laws as that in large rivers. Transport theory cannot be applied directly since there is usually no bed gradation. However, it can be calculated using procedures such as the Scour and Deposition program in Appendix VII.

One technique for calculating land surface erosion is the universal soils loss equation presented in Chapter 2 of this volume. The major

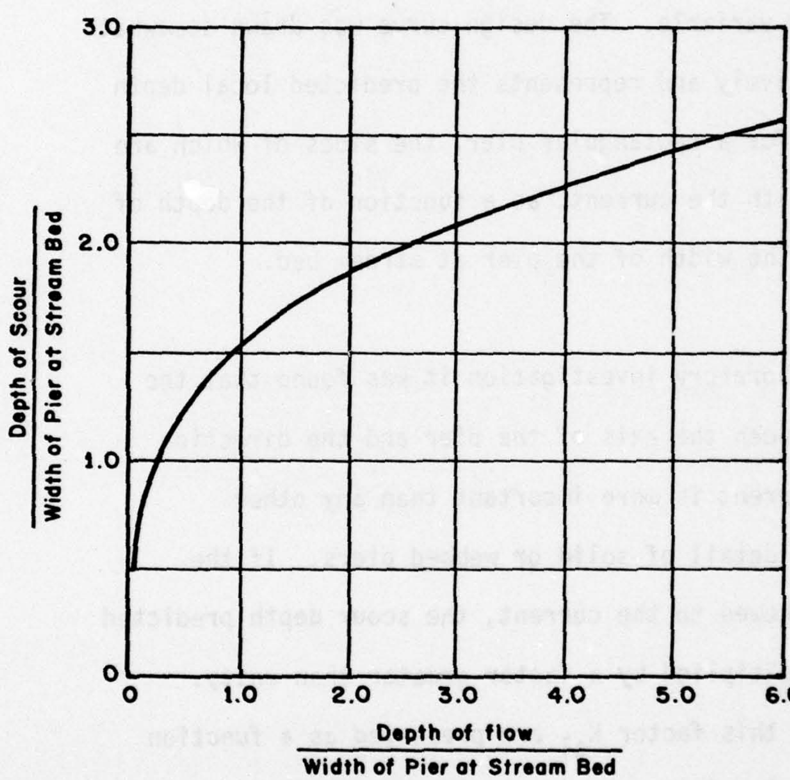
disadvantage of this technique is that transport of the sediment material is not included in the formulation. Yet, one application of the equation quickly demonstrates that erosion of the land surface is not synonymous with sediment yield from the basin. Therefore, an additional factor called the sediment delivery ratio is necessary in order to convert from land surface erosion to sediment yield at the outflow point. All of the considerations of sediment transport are included in this sediment delivery ratio factor. A better procedure would be to couple this soil erosion equation with the sediment transport models and eliminate the need for the sediment delivery ratio factor.

The use of sediment detention basins requires analytical techniques that permit the design of the size of the basin to effect a prescribed trap efficiency. The detention-time trap efficiency concept is appropriate for depositicn in the sediment basin, however, grain size of the sediment material is an important consideration, (reference 9).

Section 6.07. Local Scour at Structures

The difference between scour and degradation lies in the extent, and the trend with respect to time, of changes in the stream bed elevation. Laurson and Tock (reference 11) demonstrated that grain size was not a major factor in the magnitude of scour around bridge piers and abutments, but rather the dimensions of the pier, its alignment

with respect to the flow and its shape were the important parameters. Their basic relationship is shown in the following figure, and their concept is presented in the next few paragraphs.



Feg. 6.04. Scour Around A Pier

In using this design curve, the following information on angle of attack is pertinent:

"Local scour at piers. All of the available data were adjusted to scour conditions at a zero angle of attack for a rectangular pier and plotted non-dimensionally as equilibrium depth of scour against depth of flow with the width of pier at stream bed used as the repeating variable. The design curve was drawn somewhat conservatively and represents the predicted local depth of scour for a rectangular pier, the sides of which are aligned with the current, as a function of the depth of flow and the width of the pier at stream bed.

In the laboratory investigation it was found that the angle between the axis of the pier and the direction of the current is more important than any other geometric detail of solid or webbed piers. If the pier is skewed to the current, the scour depth predicted must be multiplied by a factor greater than unity. Values of this factor K_{a1} are presented as a function of the angle of attack and the length-width ratio of the pier at stream bed." (Reference 11, p. 42)

Angle of attack and pier shape information are shown in the following figure and table.

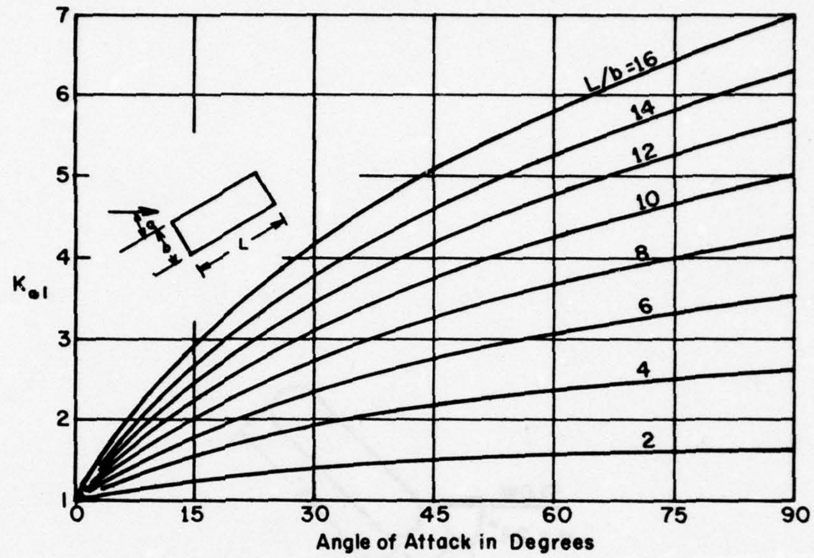


Fig. 6.05. Multiplying Factor for Angle of Attack

TABLE 6.01.

Shape coefficients K_s for nose forms

(To be used only for piers aligned with flow)

NOSE FORM	LENGTH-WIDTH RATIO	K_s
Rectangular		1.00
Semicircular		0.90
Elliptic	2:1	0.80
	3:1	0.75
Lenticular	2:1	0.80
	3:1	0.70

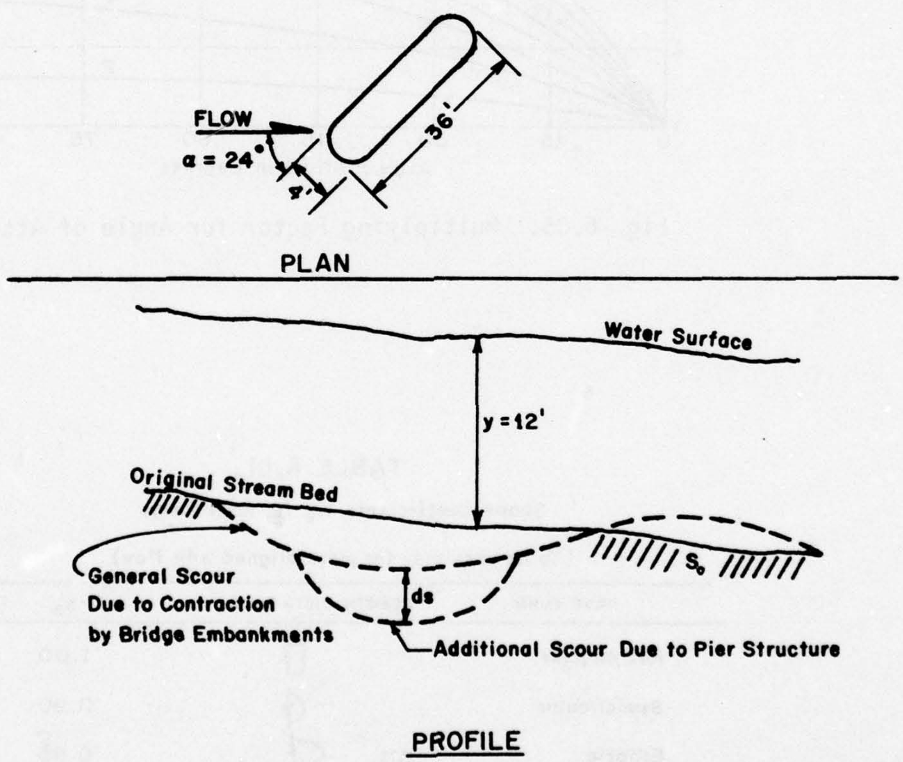


Fig. 6.06. Scour at Bridge Piers and Other Obstructions

Consider, as an example application, fig. 6.06 which shows a round nose pier having a width of four feet and located at an angle of 24° to the approaching flow. The pier is 36 feet long. The water depth, corresponding to a flood frequency of 25 years recurrence interval, is 12 feet.

Entering fig. 6.04 with y/b equal to 3.0 results in a ratio of d_s/b equal to 2.1. Adjusting for pier angle requires entering fig. 6.05 at 24° with a L/b ratio of 9. The resulting correction factor is 2.6.

The depth of scour can now be calculated as

$$\begin{aligned} d_s &= K_{a1} \cdot (d_s/b) \cdot b \\ &= 2.6 \cdot 2.1 \cdot 4 \\ &= 22 \text{ ft.} \end{aligned} \tag{6-02}$$

Note that the pier shape coefficient, K_s, is only utilized when the angle of attack is zero.

This water depth does not necessarily cause the most severe condition of scour. In fact, a range of depths should be tested. The following table presents the probability of at least 1 occurrence of the design flood during the design life of a structure. (Reference 11, page 46).

Table 6.02. Chance of 1-Occurrence of the Design Flood

Design Life, Years	Exceedance Frequency, Years 25	50	100
25	.64	.40	.22
50	.87	.64	.39
100	.98	.87	.63

These data are useful for interpreting the relative severity of the scour problem when a range of floods is utilized.

Turbulence in the flow has a major impact on scour. However, just the effect of the pier on concentration of flow is substantial. When the unit discharge increases due to deflection of flow around the pier, point velocities also increase. This redistribution of flow contributes substantially to the local scour problem. The design curves presented earlier contain the impact of both turbulence and the redistribution of flow on scour depth.

The Scour and Deposition model in Appendix VII is not appropriate for use in determining the scour around bridge piers. It is useful, however, for establishing the stream bed elevation between the bridge abutments. The magnitude of local scour due to the presence of the pier is in addition to and measured relative to this general bed elevation between the bridge abutments.

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a — Shortest axis of a sediment particle.

A_B — Cross sectional area of channel flow.

b — Intermediate length axis of a sediment particle or pier width or diameter for local scour calculations.

B — Top width.

c — Longest axis of a sediment particle.

C — Factor for converting ppm to mg/l.

C_d — Drag coefficient.

C_f — Cropping factor in the Universal Soil Loss equation.

C_s — Concentration of suspended sediment, mg/l.

d — Sieve diameter of a sediment particle.

D — Water depth.

d_{go} — The particle diameter for which 90 percent of particles, by weight, in the sample are finer.

D_s — Depth of local scour at a bridge pier.

DW — Dominant water depth calculated for obtaining the dominant water discharge.

D50 — The grain size at which 50 percent, by weight, of the sediment grains are smaller.

g — Acceleration of gravity.

G — Bed load transport in tons/day, dry weight.

G' — Total bed load transport in metric tons/sec, or lbs/sec, submerged weight.

G'' — Bed load transport in metric tons/sec/meter of width, submerged weight.

h — Gage height.

k — Coefficient for converting volume per second to weight per day.

K — Sediment load weighted by flow depth and class interval in dominant discharge calculations.

K'	Consolidation coefficient for silt deposits.
K''	Consolidation coefficient for clay deposits.
K_{al}	Coefficient for angle of attack between flow and bridge pier for analyzing local scour.
K_B	Strickler roughness coefficient, $m^{1/3}$/sec.
K_e	Soils erodability in the Universal Soil Loss equation.
K_G	The grain roughness, $m^{1/3}$/sec.
K_s	Coefficient for pier shape for analysis of local scour.
L	Length term specifically defined where used.
m	Time interval in days during which the stage was within class interval Δh in the dominant discharge calculations.
n_B	Manning n-value for grain and form roughness in channel.
n_G	Grain roughness.
p	A dimensionless coefficient defined by equation 3-08.
P_e	*Erosion control factor in the Universal Soil Loss equation.*
ppm	Parts per million.
Q	Water discharge.
Q_B	That portion of the total water discharge which is responsible for bed load transport.
Q_D	Dominant discharge.
Q_K	A dimensionless coefficient in the Meyer-Peter and Muller equation, defined by equation 3-13.
Q_s	*Sediment load.*
Q_{si}	Inflowing sediment load.
Q_{so}	Outflowing sediment load.
$\mathbb{R}$	Reynolds number.

R_B	Hydraulic radius of flow on channel bed.
R_e	Rainfall energy in the Universal Soil Loss equation.
S	Energy slope or storage capacity.
T_d	Detention time or flow through time.
T_e	Trap efficiency.
V	Average velocity of flow.
V_d	Total sediment delivered to a reservoir during the project life (50 or 100 years).
w	Fall velocity of a sediment particle.
Y_e	Potential sediment yield from land surface erosion of a test plot.
Y_w	Average annual water yield.
γ	Specific weight of fluid.
γ'	Initial, submerged unit weight of a silt deposit.
γ''	Initial, submerged unit weight of a clay deposit.
γ_s	Specific weight of a sediment particle.
γ_s''	Submerged specific weight of sediment particles ($\gamma_s-\gamma$).
γ_{sand}	Submerged unit weight of a sand deposit.
γ_T	Representative unit weight of a sand/silt/clay deposit T years after deposition occurred.
Δh	The class interval assigned to water stage in the dominant discharge calculations.
ν	Kinematic viscosity of fluid.
ρ	Density of the fluid.
ρ_s	Density of a sediment particle.
σ	$(\rho_s-\rho)/\rho$.
τ	Tractive force on stream bed.

APPENDIX 3

CORPS OF ENGINEERS METHODS FOR PREDICTING SEDIMENT YIELDS

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Oxford, Mississippi on
28 - 30 November 1972

CORPS OF ENGINEER METHODS FOR PREDICTING SEDIMENT YIELDS

By Robert H. Livesey 1/

INTRODUCTION

The methods used by the Corps of Engineers for predicting sediment yields are, in general, based upon empirical relationships but vary in scope and procedure depending upon the complexity of the individual water resource project plan or design. Due to the diverse nature of these projects, both in design magnitude and geographic location, a standard method approach for design application is not employed throughout the Corps. Instead, the individual District Offices make a sensitivity appraisal to evaluate the impact of all sedimentation influences on a specific project plan. From this first approximation analysis, the scope of the sedimentation problem is defined. This definition then becomes the basis for selection of feasible methods to be used in establishing the true magnitude of the problem components and design solution criteria. Where it is apparent that modification of a method might be practical to produce an improvement in design evaluation, such modification is encouraged. For this reason, a variety of procedures are developed and employed throughout the Corps but they all relate closely to one of the three basic empirical approaches for predicting sediment yield; namely (1) measuring the yield rate directly by sediment sampling or reservoir surveys, (2) extrapolation of such measured data to unmeasured drainages by various correlation and probability techniques, or (3) establishment of identifiable physiographic watershed or stream

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flow characteristics that permit development of predictive equations. Theoretical approaches to the prediction of sediment yields have been occasionally employed for special circumstances where empirical relationships were weak or confidence lacking but such procedures are not common.

DEVELOPMENT OF PREDICTION METHODS

The earliest record of sediment sampling in the United States dates back to 1838 when the Corps of Engineers was engaged in navigation channel work on the lower Mississippi River. During the next 100 years, the need for sediment predictions related almost entirely to river navigation or estuary maintenance work. It was not until after passage of the Flood Control Acts of 1928 and 1936, when the Corps started the planning, design and construction of multiple purpose reservoirs, that the need for sediment yield predictions developed. Typical of this initial phase of sediment yield investigations was STRAUB'S work that is well documented in the 1933 Missouri River Basin 308 Report. His development of the sediment rating curve method was later amplified by CAMPBELL and BAUAER in the 1940's, and MILLER in the 1950's, into the popular rating curve-flow duration method. After STRAUB'S 308 work the emphasis on documenting sediment yield rates shifted in the 1940's to reservoir survey measurements and the relation of sediment yield to contributing drainage areas, reservoir capacities, stream density or slope, and runoff. The early work of BROWN and GOTTSCHALK is typical of this

period. But this work, like STRAUB'S, was considered professionally weak because it related sediment yield to only a few of the many contributing factors. Next, during the early 1950's, efforts were concentrated on the expansion of MUSGRAVE'S definition of quantitative factors for small land units to the drainage increments of large river control projects. These evaluations attempted, without much success, to relate many of MUSGRAVE'S factors on a regional or annual basis in lieu of local or seasonal definitions. During this same period, sediment sampling and reservoir survey measurement techniques were enhanced. Long term basin runoff characteristics were also identified to improve confidence in the sediment rating curve - flow duration method. However, by the late 1950's, a shift in project planning to smaller drainage areas started. The definition of local drainage controls and urban runoff assumed greater importance; the "big dam" criteria for yield predictions was no longer vogue. This change required a downward extrapolation toward the upper limits of SCS criteria. To meet this need, the number of Corps sediment load stations were doubled, plans were implemented to document urban runoff characteristics and correlation techniques concentrated on qualifying the adequacy of short term records. As the environmental issues of the late 1960's developed their impetus, design criteria and needs mushroomed into the broad fields of water quality control, biological reproduction, eutrophication acceleration and most recently wastewater management. The proper prediction methods for most of these latter aspects remain unqualified at the present time.

PREDICTION CRITERION

Corps' study investigation or design criterion for individual projects dictates that alternative methods for sediment yield prediction be considered and evaluated. These empirical methods generally fall into two basic categories: (1) the extrapolation of measured records and (2) the use of predictive equations. Most work related to the planning, design and operation of reservoirs is based upon the former method while channel alignment and stabilization aspects relate to the latter method. Although the Corps has no standard method, the use of the sediment rating curve - flow duration technique, or some ramification, has had the widest application. Prior to discussing the characteristics of various methods, some comment must be focused on the appraisal techniques which precede the selecting of the alternative methods to be considered. The following are common project evaluation criteria:

1) Sensitivity Evaluation. This appraisal attempts to bring the scope of sedimentation influences into focus with the over-all project purpose and plan. Later detailed analyses define the real magnitude and occasionally dictate a shift in study emphasis; but, early in both the planning and design phases, all potential problems are identified and priorities established regarding their importance to the various design features. When considering current environmental aspects, it is not uncommon to schedule a later, second sensitivity evaluation in case a re-orientation of project priorities or efforts is necessary.

2) Identifying Basic Data. This operation consists of a records and literature search to identify available streamflow or sediment measurement records, previous related study data or pertinent research activity work.

3) Hydrology. This analysis usually constitutes the initial design effort. Early in this work preliminary sediment yield predictions are made to satisfy first approximation storage and flow routing requirements. Later, as alternate project operation schemes are developed, the design yield rates are incorporated into the final hydrologic analysis. The development of long-term flow-duration data is another important contribution.

4) Geomorphic Characteristics. The factors considered in this analysis are quite varied and broad; the degree of investigation depends upon need. General needs include such items as geologic variations, soil classifications and characteristics, channel dimensions, composition of stream bank and bed materials and stream slopes.

5) Basin Reconnaissance. At least one field reconnaissance of the contributing drainage is made early in the preliminary design phase. Usually it is a "wind shield" type survey of sufficient scope to identify major or contrasting features of the drainage and permit judgment comparison of variations in yield rates and channel dimensions.

PREDICTION METHODS

The following discussion of the various sediment yield prediction methods used in Corps of Engineer studies and designs will be divided into the two basic categories previously mentioned. Descriptive comments will be limited to a summary nature but a study or design memorandum reference is given for each method. Most references can provide complete details on one or more methods. An attempt was made to include with each discussion a reference plate which identified the salient features of the method or the output results.

The first category involves the extrapolation of measured records and is divided into the three major measurement classifications: sediment loads, reservoir surveys and reconnaissance inspections. Relevant methods for each include:

1) Sediment Load Measurements

a) Sediment Rating Curve Method. This basic, older method is usually associated with a flow-duration analysis but occasionally special circumstances still require its use. An example would involve instantaneous units of flow and concentration rather than mean daily values. These applications usually relate to a near constant or limited range of flows, such as for seasonal or monthly variations between run-of-river reservoirs within a large system. In such instances the minor incremental flow and sediment contributions, including their duration and frequency, are usually obscured by the large base flow. The method involves the plotting of measured suspended sediment load values versus equivalent units of discharge for desired time periods and defining the mean curve. An example is shown in Figure 1. The original use of this method was developed for the 1933 Missouri Basin 308 report with further enhancement by CAMPBELL and BAUDER in their paper, A Rating-Curve Method for Determining Silt-Discharge of Streams as published in Transactions American Geophysical Union, Volume 30, August 1949.

b) Sediment Rating Curve-Flow Duration Method. This popular method combines the above rating curve principle with the measured stream-flow record to develop a probability correlation between the sediment and water discharge of a stream. The method consists of a

determination of suspended sediment load values from the rating curve for corresponding increments of discharge from a flow duration curve. Multiplication of the suspended sediment load and discharge increments by the time percentage interval gives a daily occurrence value. Totaling these daily average values produces the mean daily discharge and suspended sediment load for the year. Further multiplication of these mean daily values by the number of days in the year gives average annual rates. Addition of unmeasured suspended or bed load estimates results in a total average annual sediment load value. Variations in this method permit development of long-term rate estimates based upon seasonal or short periods of record. Figures 1, 2 and 3 record the principal details of this method. For more complete details, including an evaluation of the techniques of this method, see An Analysis of the Flow-Duration, Sediment-Rating Curve Method of Computing Sediment Yield by Carl R. Miller as published by the Bureau of Reclamation in April 1951.

c) Sediment Discharge-Soil Type Relationships. This method relies upon a runoff-sediment load record to obtain a correlation of sediment yield according to soil classification and cultivated areas. River basins are divided by soil types and annual surface runoff-sediment discharge curves developed for each classification according to the degree of cultivated acreages. An example of the relationship developed for 13 drainages of mixed loess and glacial soils is shown in Figure 4. A comparable correlation was possible for residual limestone, sandstone and shale soils but in loessial terrain the results were indeterminate. For further information refer to an unpublished report

on Rates of Sediment Production in The Kansas City District by A. L. Hill.

d) Dominant Basin Characteristics. The similarity of the dominant physical characteristics of a drainage basin versus the measured sediment production is the basis for this method. The dominant characteristics included land use, relief and topography, climate, water and soil types. Land resource areas are used to group the defined individual sediment yield rates into comparable area categories. Both suspended sediment load and reservoir sedimentation survey records are used to establish yield rates by drainage area or time increments for a given base period. The flow-duration principle is applied to adjust short-term records to the base period. Such adjustments require establishment of sediment discharge to streamflow relationships for the period of measurements and then correlating this data to the long-term flow regimen of the stream. The method has produced indications of sediment yield trends with time in several instances. Figures 5, 6 and 7 depict the general features of this method. For details see Sediment Yields in the Upper Mississippi River Basin by Frank J. Mack as published in Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs in April 1970 by the Hydrologic Engineering Center, Corps of Engineers at Davis, California.

e) Sediment Yield by Isogram Intervals. Except for the degree of individual basin analysis, a similarity exists between this and the preceding method. This method recognizes the dominant physical characteristics and measured sediment production records of the basin, but, in addition, relies upon personal knowledge and engineering

judgment to evaluate the sediment yield characteristics of a basin. The method was developed for use as a task force expedient by a group of inter-agency sedimentation specialists to document sediment yield rates for large river basins. Yield rates for standard periods of time are derived by extrapolation of shorter period records by one of three procedures; comparing sediment load-water discharge relations between periods of record and the standard period, derivation of sediment-water regression curves for increments of drainage area or evaluating relations between intermittent sediment measurements made over short-time periods. The final delineation of isogram lines are based upon group experience and judgment. A typical end-product of this method is shown on Figure 8. Examples of this method can be found in any one of the seven sub-basin sedimentation reports prepared by the Task Force on Sedimentation for the Missouri River Basin Comprehensive Framework Study, as submitted to the Missouri Basin Inter-Agency Committee in 1968 and 1969.

f) Sediment Yield During Urban Expansion. The techniques of this method are still in the developmental stage. The basic premise concerns transition of rural lands to urban usage over given time periods. It assumes that sediment yield rates accelerate from agricultural values to a high peak during landscaping or construction, then decline to a lower plateau as the land "heals" and finally level off at some low stable rate representative of business or residential lands. A projection of urban expansion limits, as provided by the local metro planning authority, serves as a base for converting contributing drainages from rural use to single family, multi-family

or commercial usage. Integration of varying yield rates for area increments under various stages of development permits a continuous assessment over the design life of the project. Judgment extrapolation of limited urban runoff and sediment yield measurements is currently necessary but data collection programs that concentrate on storm runoff measurements can quickly improve this limitation. A generalized schematic outline of this method, as being developed by the Omaha District, is shown in Figures 9 and 10.

2) <u>Reservoir Sedimentation Surveys</u>

a) <u>Sediment Yield Per Unit of Drainage</u>. The application of this method is common because of its simplicity in relating measured rates of sediment yield to the contributing drainage area increment. Numerous correlations are possible within certain ranges of drainage area by soil types, runoff volumes, watershed-capacity ratios, dominant discharge, land use, physiographic areas and many other parameters. Most Corps applications of these yield rates pertain to contributing drainages greater than 100 square miles so correlation with the conventional soil loss parameters is not common. The principle source of reference data is ARS Misc Publication No. 1143, <u>Summary of Reservoir Sediment Deposition Surveys Made in the United States through 1965</u>, or related reporting Form 1787. A typical example of this method can be noted in Figure 11.

b) <u>Yield Production for Debris Basins.</u> This is a special application used to determine the sediment yield into flood control

debris basins in mountainous type terrain. The method was developed from observed debris volumes that reflect ground conditions influenced by prior rain runoff and areas subjected to partial or complete "burns." Influencing factors include size and shape of drainage area; steepness of canyons and side slopes; geological characteristics; type and density of plant cover; recency of burns; and frequency, duration and intensity of storms. Measured debris volumes are adjusted to a common base and curves developed for separate corrections of the major factors affecting debris production. Figure 12 summarizes the details of this method. Further information is available in A New Method of Estimating Debris-Storage Requirements for Debris Basins by Fred E. Tatum as published in the Proceedings of the 1963 Federal Inter-Agency Sedimentation Conference, ARS Misc. Pub. No. 970.

3) Reconnaissance Inspections. The following methods are directed toward establishing preliminary estimates of sediment yield for large drainage areas. On occasion, the investigation details have been expanded to cover studies of design scope for small to moderate drainages. Their basic premise consists of a quick but detailed reconnaissance type inspection of the contributing drainage area by two or more Sedimentation Specialists who, by experience, are capable of making judgment estimates of sediment yield rates. During the field reconnaissance they collectively establish representative point rates for incremental portions of major drainages within the over-all study basin. This technique is particularly applicable for a degree assessment of contributing versus non-contributing drainage as influenced by soil

management practices, smaller reservoirs or ponds or irrigation diversion projects. If the basin is relatively small, perhaps less than 1000 square miles, the estimates for even third or fourth order streams can become quite detailed. For larger basins, selected streams might be covered in more detail and the remainder left to a random choice of inspection. The end product is usually similar to that shown in Figure 8.

a) Interpolation of Rates Within a Basin. This method requires several points of measured sediment yield, by either sediment sampling or reservoir surveys, within the basin drainage. One of these points should be located near the mouth of the basin to reflect the total measured yield from the drainage. During the field reconnaissance these measured rates are used as a comparative guide for estimating yield rates for small increments of the unmeasured drainages. When sufficient point estimates are established, a yield contour map is developed. Using digitizing or planimetering processes, drainage area increments of equal yield rates are totaled for the major drainages within the basin. A summation of these totals and division by the contributing drainage area value gives an average sediment yield rate for the subject increment. These increment rates are checked against the measured increment rates for verification. If they are not comparable within reason, adjustments to selected point estimates are justified to bring the integrated total into balance with measured data.

b) Extrapolation to Unmeasured Watersheds. The basic procedure is similar to that above except that a comparison between the

total estimated and measured rates for a basin is not possible. Prior to the field inspection of the unmeasured drainage, the reconnaissance team usually makes a preliminary inspection of the measured drainages being used as the extrapolation base. This visual inspection requires additional time and effort but serves as an effective means for comparative extrapolation. The validity of this method is dependent upon the degree of extrapolation but apparent satisfactory results have been produced within a restricted time period.

The second category involves predictive equation methods. Most of the individual methods discussed below apply to the solution of specific problems. They differ from the preceding methods in that the predicted sediment yield relates primarily to channel contributions rather than from a watershed drainage. The Corps use of predictive equations for determining watershed yields is very limited.

1) Sediment Transport Relationships. There are a variety of methods in this classification but the most common is the EINSTEIN approach, with one of its many modifications, or the more recent TOFFALETI procedure. Their connection with sediment yield predictions usually relate to channel stabilization projects involving aggradation or degradation problems. But their application is also common in establishing the magnitude or rate of unmeasured suspended or bed sediment load values. Estimates of such values are extremely important in certain instances when establishing yield rates from measured suspended sediment load records, such as is required in the

rating curve-flow duration method. An excellent discussion of the EINSTEIN and TOFFALETI methods, plus others, and a listing of complete references can be found in the Journal of the Hydraulics Division, ASCE, April 1971, under Paper 8076 titled Sediment Transportation Mechanics: Sediment Discharge Formulas

2) Detention-Time Method. This method is used to predict the volume of sediment passing through a series of run-of-the-river type reservoir projects. It is based upon empirical relationships between the detention time of flows passing through the reservoir system and the percentage of sediment deposited. Detention time is defined as the ratio of reservoir storage to the inflow discharge at any given time. Curves of detention time versus percent of wash load and bed material load deposited are developed to determine deposition-flow through volumes for incremental reaches. As the reservoir volume is depleted by deposition, the detention time is reduced and the yield rate per unit of flow increases. Figure 13 shows a typical relationship between detention time in hours and percent of load deposited for a series of reservoirs. Reference details for this method can be found in Dardanelle Reservoir Design Memorandum No. 6, Part IV Sedimentation prepared in October 1957 by the Little Rock District.

3) Hydraulic Elements. This is another method for determining run-of-the-river reservoir yield rates. Individual reservoirs are divided into reaches and hydraulic elements are determined for various discharges by back-water computations. The sediment load is then related to the velocity, depth and slope, or a combination of such elements. The inflow-outflow sediment loads are computed on a step procedure from reach

to reach with backwater computations repeated as necessary to obtain new hydraulic element values as deposits accumulated with time. The method is time consuming but permits recognition of the individual element changes or trends, an example is shown in Figures 14 and 15. (Note: These figures could not be reduced in size and consequently are not included. The method depicted is embodied in the computer program presented in Appendix VII of this volume. W. A. Thomas) The reference for this method is the same as given above for the detention-time method.

4) Bank Caving-Wash Load Yields. This is another special application method used to estimate the excess rate of bank-caving over bank building relative to an increase in the wash load being transported. It applies, again, to run-of-river reservoirs where the erosion of concave banks in bends may continue at the natural high flow rates due to the duration of artificial bank full stages under operating conditions. The change in bank caving-bank building equilibrium produces an additional supply of wash load due to channel widening. The method is admittedly over-simplified for the complex phenomena of bank caving but it offers a systematic method of recognizing the increase in wash load due to bank caving. An example of this method is given in Figures 16 and 17. Reference details can be found in a Supplement To Dardanelle Reservoir Design Memorandum No. 6-4 prepared by the Little Rock District in January 1959.

5) Sediment Delivery Ratio. This category covers both the sediment delivery and sheet erosion prediction methods developed by the Department of Agriculture. The application of these methods to Corps projects is generally limited to small watersheds of less than 25 to 50 square miles. Adoption of the MUSGRAVE equation is probably still preferred over the Universal Soil Loss equation for smaller drainages. However, more useful are the various empirical equations developed by such authors as ANDERSON, BARNES, BRUNE, GLYMPH, GOTTSCHALK, HEINEMANN, KOHLER, MANER, PIEST and others. Due to the limited application of these methods, reference is made to the following sources for precedural details: Studies of Sediment Yields From Watersheds by Louis Glymph or Sediment Sources and Sediment Yields prepared by Robert F. Piest as Chapter IV of the ASCE Manual on Sedimentation Engineering and published as paper 7337 in the Journal of the Hydraulics Division, June 1970.

6) Tailwater Degradation. Several methods are included in this grouping. Their principal function is to predict degradation trends; but, as part of the computational procedure, sediment yield values for the degrading reach are developed. Factors considered in their application include composition of the bed material and its coarsening with time, the magnitude of future flows and changes in flow characteristics such as channel shape, depths, velocity and slope. Three common methods include use of the EINSTEIN bed load function for sediment transport; use of the KALINSKE formula to compute bed load plus

the development of relationships between natural and modified bed material load transport as degradation progresses; and determination of the thickness of an armor layer and the depth of scour at which this layer would form. This latter technique assumes degradation would cease when a layer of "non-moving" particles forms a sufficient armor to prevent the effective leaching of finer particles from the underlying bed material. Procedural details on these methods can be found in a paper on Sedimentation Studies for Robert S. Kerr Lock and Dam, Arkansas River Basin by Howard O. Reese as published in the Hydrologic Engineering Center's Proceedings of a Seminar on Sediment Transport in Rivers and Reservoirs, April 1970.

FUTURE NEEDS

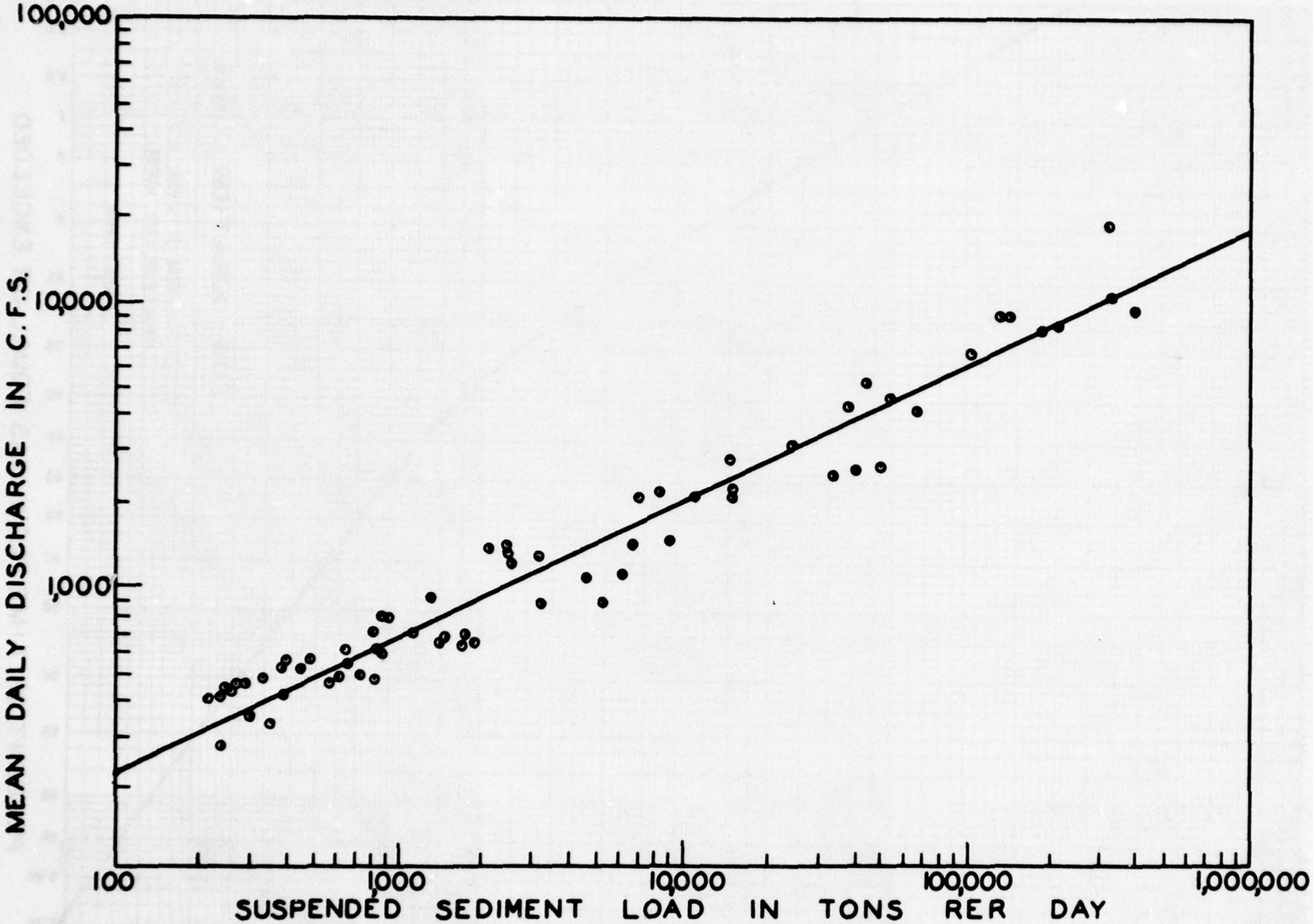
During the past decade a shift in emphasis has taken place within the Corps regarding the need for sediment yield predictions. Prior to the mid-1950's, sediment was viewed primarily as a malignant growth that reduced the effectiveness of reservoirs, floodways, navigation channels and harbors. This was also the period of "big dam" planning and construction where sediment depletion rates played a relatively minor role in design because of the voluminous storage allotted for multiple purpose use. The need for sediment yield predictions for large drainage areas has essentially vanished. As an indication, about 15 years ago the Corps was operating 135 sediment load stations with 43% having drainage areas greater than 5000 square miles, 27% in the 500-5000 range and 30% less than 500 square miles. Presently this number

of stations has doubled with a comparative shift in percentage ratio of 25:37:38. Almost half of the current stations are operated for planning or design purposes. For example, during 1969 the Corps had under construction 23 reservoir projects for hydro-electric power and flood control, 64 reservoir projects for flood control and multi-purpose use and 84 local flood control protection projects. Now the Corps emphasis seems to be focused on projects with sediment contributing drainages that generally vary within the 500 to 2500 square mile range. But if our prediction approach is to continue on an empirical basis, long-term data records for drainage areas within this bracket are inadequate, particularly for reservoir survey data. It is estimated that there are some 28,000 reservoirs in the United States yet we have sediment yield records on only 4%. But more significant is the fact that of the 1200 individual reservoirs listed in the 1965 summary of reservoir survey data, 80% of the documented record ranges below 50 square miles and 90% below 500 square miles. It is apparent that, figuratively speaking, a scarcity of data exists in the no-man's land that is bracketed with voluminous SCS records on the low side and adequate Corps, USBR and TVA experience on the high side. In essence, the basis for future Corps yield predictions by empirical methods will be somewhat handicapped until data records within this bracket are expanded by measurements or enhanced by correlation techniques.

Today, the dirty word "sediment" has dual connotations; it must now be recognized from both a beneficial and detrimental point of view. On one hand sediments rank as a major cause of water pollution, but on the other hand they play a dominating role in water quality control

due to their assimilation capabilities. Apparently they also serve similar dual roles as catalytic or transporting agents in physical, chemical or biological processes. With the current focus of Corps activities in areas of environmental control, urban development or expansion and wastewater management, the recognition of such aspects is receiving prime attention in planning and design. But unanswered questions continue to outnumber even qualified answers. There is an unquestionable need for further amplification of key sedimentation influences in certain environmental processes before proceeding with detailed planning or design applications.

The immediate needs of the Corps of Engineers in expansion of sediment yield prediction methods will probably be focused along these two major channels: 1) definition of empirical relationships for drainage areas of moderate size, and 2) establishment of the role sediments play in the complex environmental processes. The application of computer-oriented methods for mathematical simulations or modeling will undoubtedly play a key role in the solution of some of these problems. Past experience however, has clearly demonstrated that one or two standard methods or universal equations, regardless of their complexity, will not meet the diverse needs of modern day engineering, planning or design. For this reason, our efforts will continue to concentrate along the lines of practical needs to resolve particular problems. But in doing so, we intend to also continue our policy of improving available methods or techniques by modification, regardless of their degree of sophistication, as the needs of the problem warrant.



SEDIMENT RATING CURVE
ELKHORN RIVER
WATERLOO, NEBR.

FIGURE 1

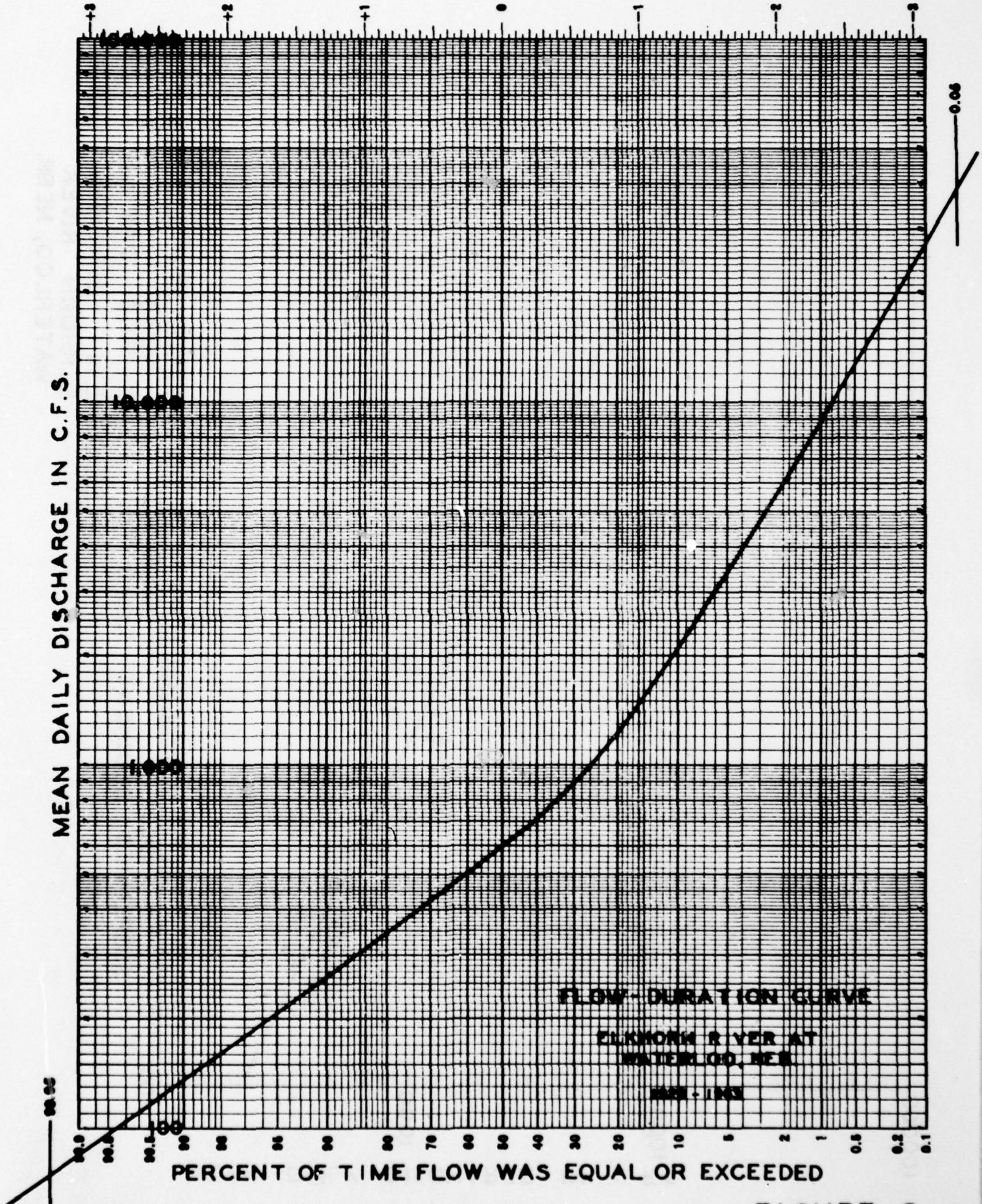

MEAN DAILY DISCHARGE IN C.F.S.
10,000
1,000
100
PERCENT OF TIME FLOW WAS EQUAL OR EXCEEDED
FLOW-DURATION CURVE
ELKHORN RIVER AT
WATERLOO, NEB.

FIGURE 2

RATING CURVE - FLOW DURATION METHOD

LONG TERM TOTAL SEDIMENT LOAD ESTIMATE FOR ELKHORN RIVER AT WATERLOO, NEBRASKA

STREAMFLOW RECORD - 1929 TO 1963
SUSPENDED SEDIMENT SAMPLING RECORD - AUG. 1948 TO NOV. 1950

Percent Mid Ord.	Percent Increment	Water Discharge Q_w (cfs)	Suspended Sediment Load Q_s (tons)	Daily Average Q_w (cfs)	Daily Average Q_s (tons)
0.05	0.1	37,000	4,500,000	37.0	4500
0.3	0.4	15,000	680,000	60.0	2720
1.0	1.0	9,000	230,000	90.0	2300
3.25	3.5	4,500	55,000	157.5	1925
10	10	2,100	11,000	210.0	1100
20	10	1,200	3,500	120.0	350
30	10	880	1,800	88.0	180
40	10	710	1,150	71.0	115
50	10	600	800	60.0	80
60	10	510	580	51.0	58
70	10	425	390	42.5	39
80	10	345	250	34.5	25
90	10	260	140	26.0	14
96.75	3.5	180	64	6.3	2
99.0	1.0	135	35	1.4	1
99.7	0.4	105	20	0.4	0
99.95	0.1	74	13	0.1	0
		Totals		1055.7	13,409

Annual Q_w = 1055.7 x 365 x 1.98 = 762,950 AF/Yr

Annual Q_s = 13,409 x 365 = 4,894,000 tons/yr

Unmeasured & bed load = 10% Qs = 489,000 tons/yr

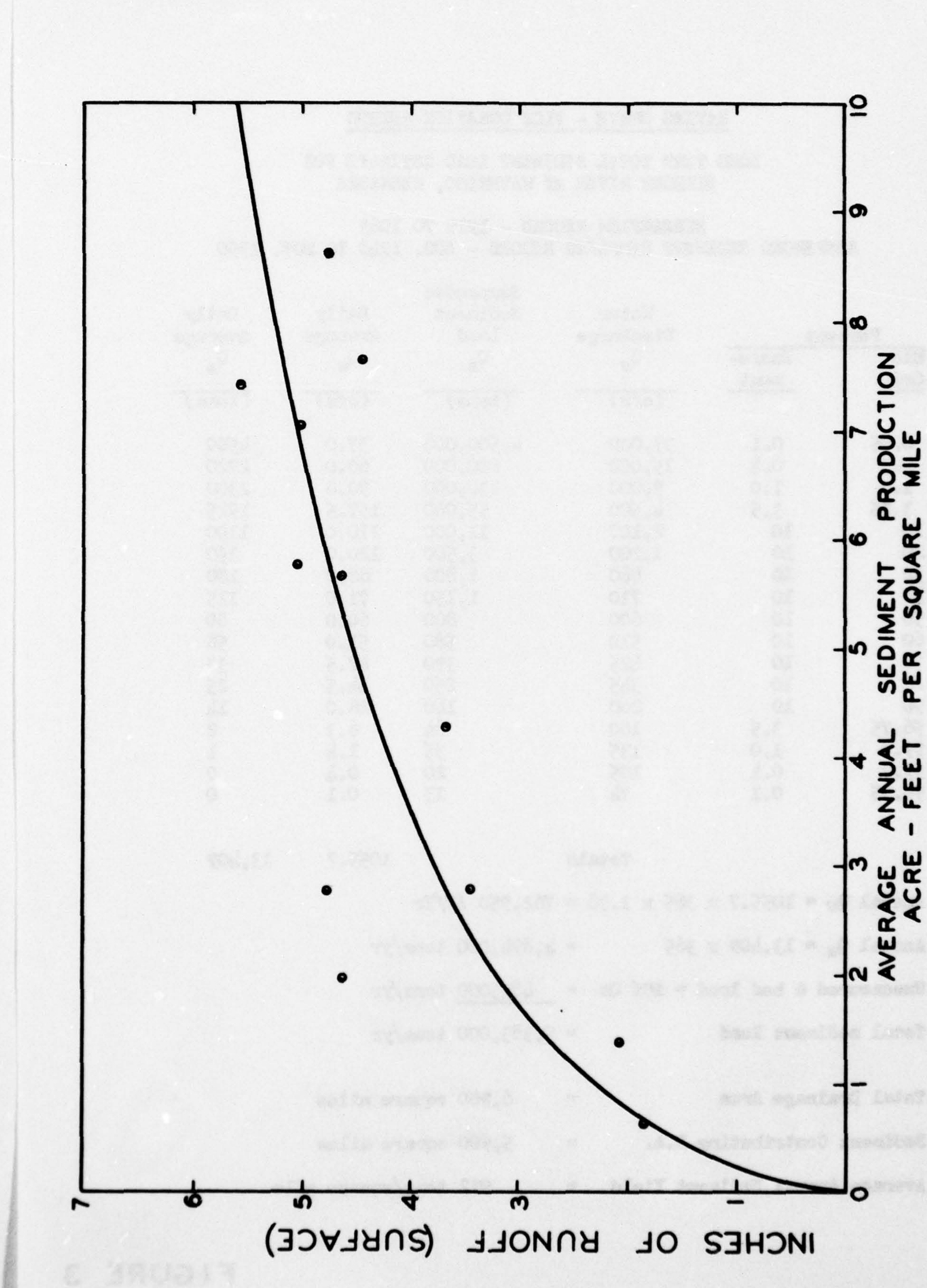
Total sediment load = 5,383,000 tons/yr

Total Drainage Area = 6,900 square miles

Sediment Contributing D.A. = 5,900 square miles

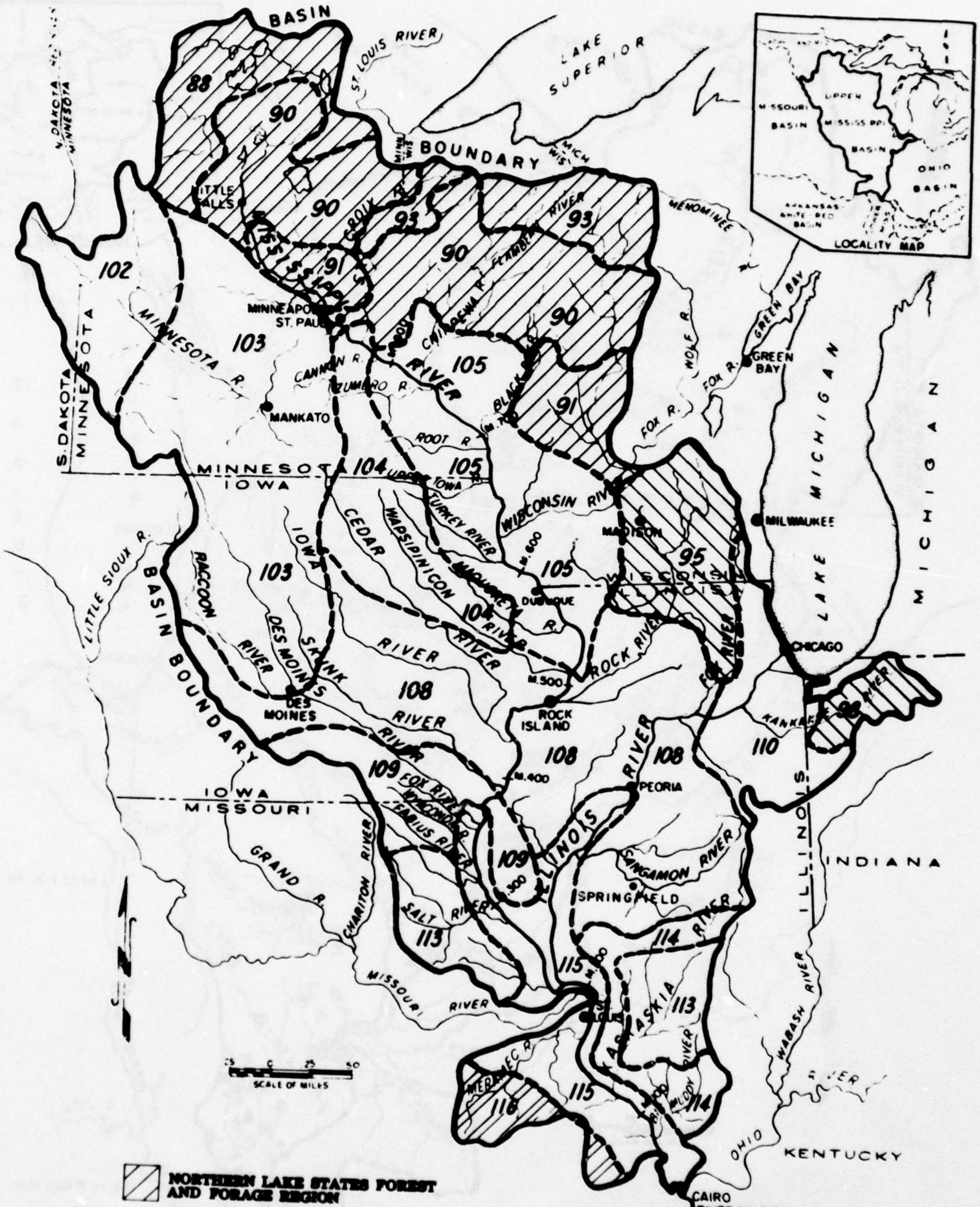
Average Annual Sediment Yield = 912 tons/square mile

FIGURE 3



AVERAGE ANNUAL RUNOFF FOR MIXED LOESS & GLACIAL SOILS

FIGURE 4



NORTHERN LAKE STATES FOREST AND FORAGE REGION

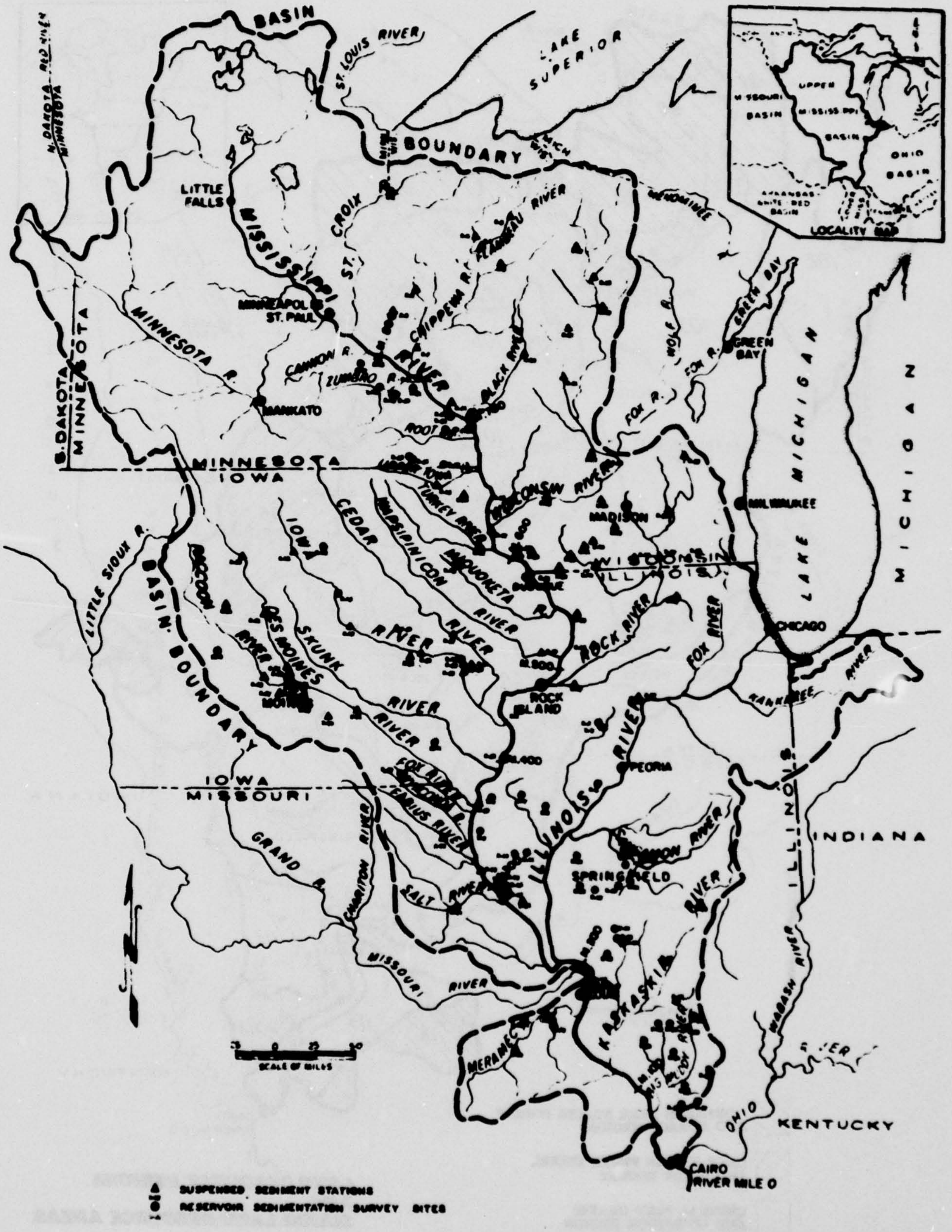
LAKE STATES FRUIT, TRUCK, AND DAIRY REGION

CENTRAL FEED GRAINS AND LIVESTOCK REGION

EAST AND CENTRAL GENERAL FARMING AND FOREST REGION

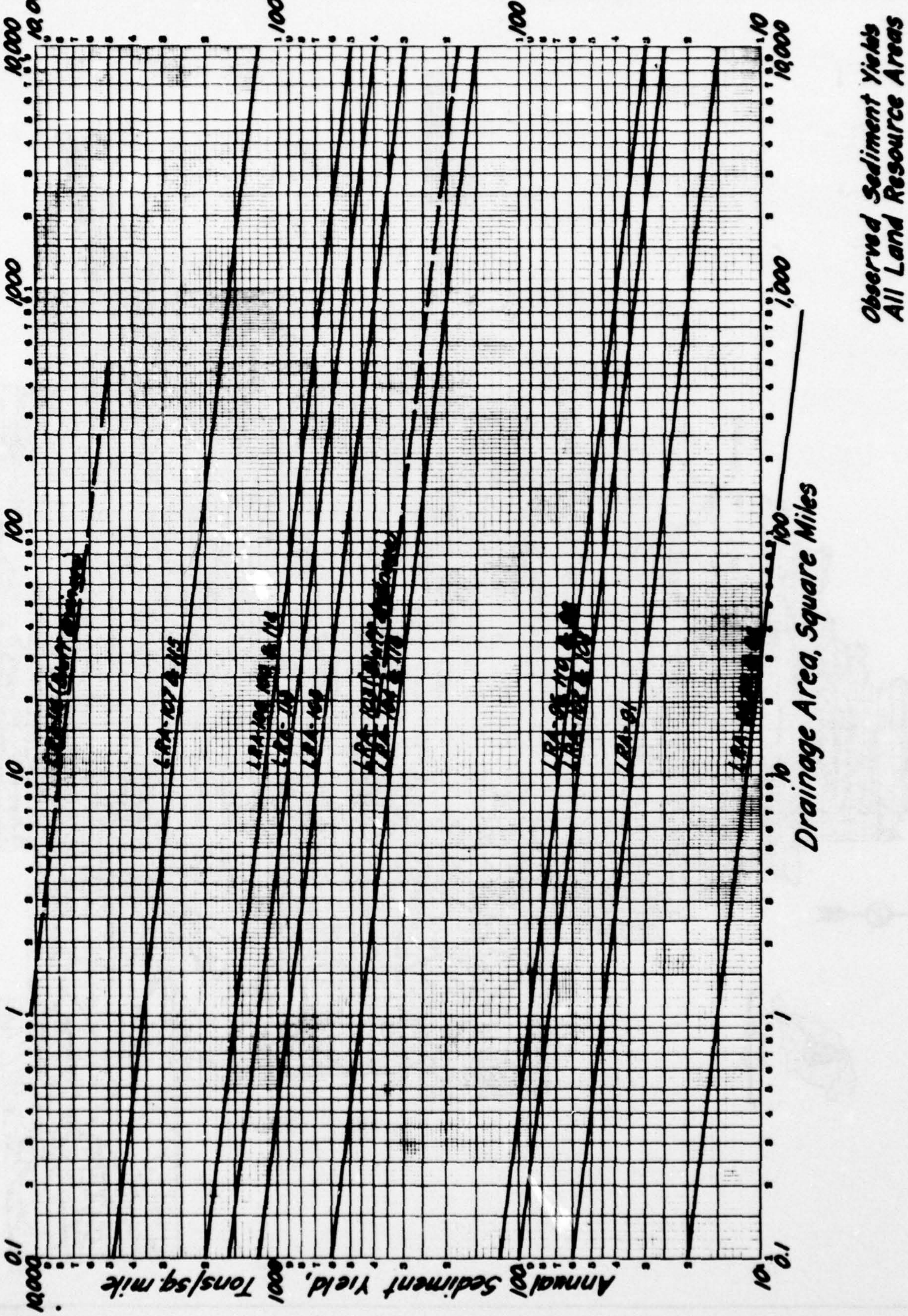
LAND RESOURCE REGIONS AND MAJOR LAND RESOURCE AREAS

FIGURE 5



LOCATION OF BASIC DATA

FIGURE 6



Observed Sediment Yields
All Land Resource Areas
Drainage Area, Square Miles
Annual Sediment Yield, Tons/sq. mile

FIGURE 7

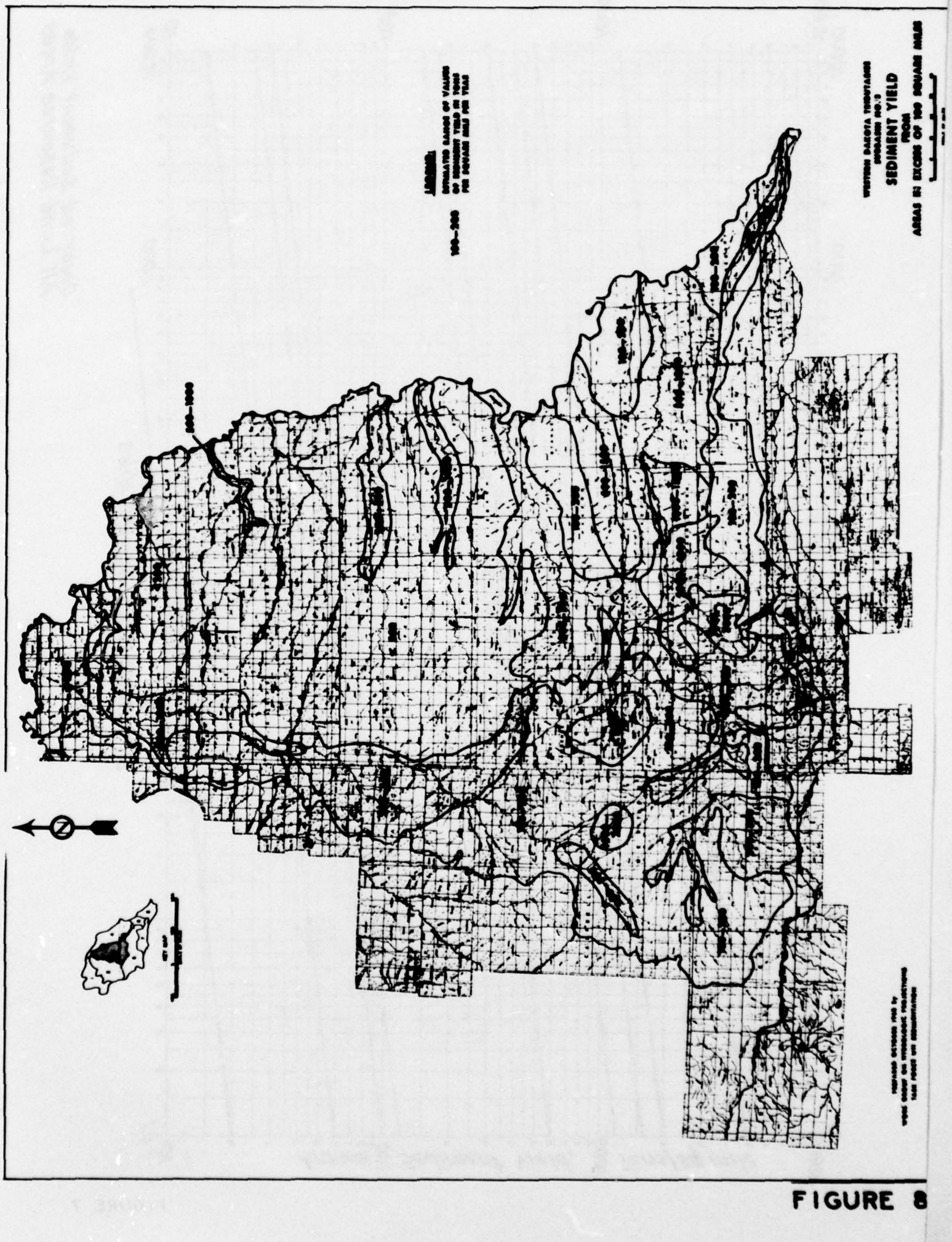
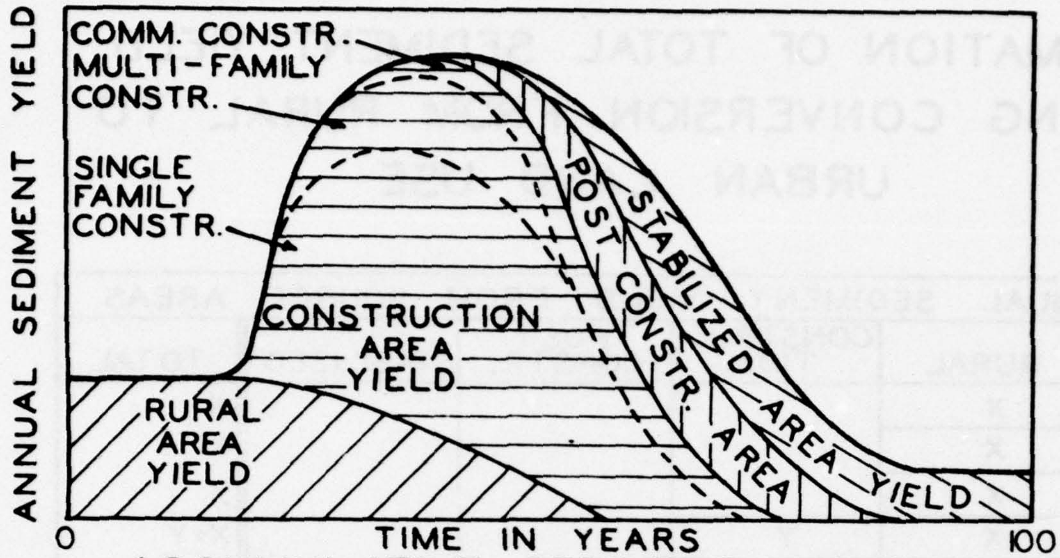
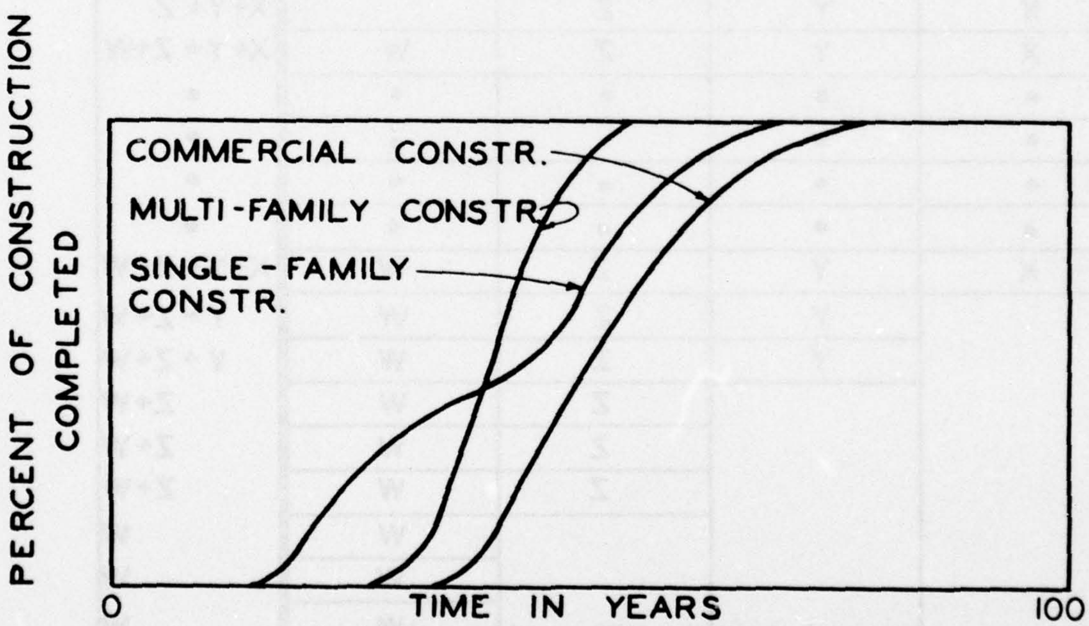

SEDIMENT YIELD
FROM
AREAS IN EXCESS OF 100 SQUARE MILES
100—200

FIGURE 8



ACCUMULATIVE SEDIMENT YIELD



LAND USE PROJECTIONS
(FURNISHED BY METRO. PLANNING AUTHORITY)

SEDIMENT YIELDS DURING URBAN EXPANSION

FIGURE 9

SUMMATION OF TOTAL SEDIMENT YIELD DURING CONVERSION FROM RURAL TO URBAN LAND USE

ANNUAL SEDIMENT YIELD FROM SOURCE AREAS					
YEAR	RURAL	CONSTRUCTION	POST CONSTR.	STABILIZED	TOTAL
1	X				X
2	X				X
3	X				X
4	X	Y			X+Y
5	X	Y			X+Y
6	X	Y	Z		X+Y+Z
7	X	Y	Z		X+Y+Z
8	X	Y	Z	W	X+Y+Z+W
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
•	•	•	•	•	•
n-8	X	Y	Z	W	X+Y+Z+W
n-7		Y	Z	W	Y+Z+W
n-6		Y	Z	W	Y+Z+W
n-5			Z	W	Z+W
n-4			Z	W	Z+W
n-3			Z	W	Z+W
n-2				W	W
n-1				W	W
n				W	W
TOTAL	ΣX	ΣY	ΣZ	ΣW	$\Sigma(X+Y+Z+W)$

FIGURE 10

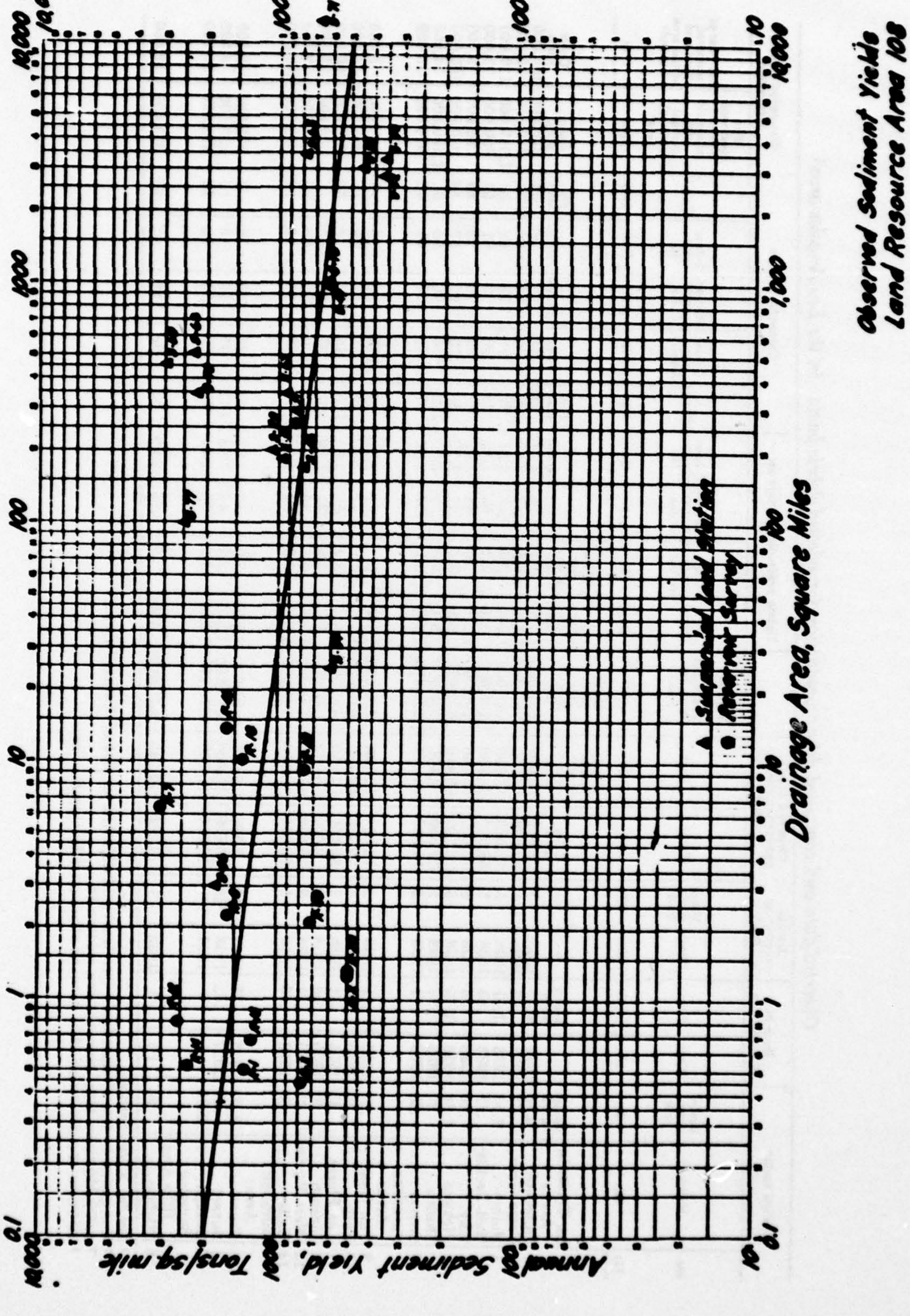

Observed Sediment Yields
Land Resource Area 108
Drainage Area, Square Miles
Annual Sediment Yield, Tons/sq. mile
Suspended Load Station
Reservoir Survey

FIGURE 11

Observed data and computed debris production for selected debris basins in the Los Angeles area[1]

Debris basin[1]			Burn in drainage area		Debris-producing flood		Observed debris production during flood		Observed debris rate adjusted to 100 percent burn 1st year[2]	Debris production factors for—				Correction factors					Computed debris production	
No.	Name	Drainage area	Year	Area	Year	Years after burn	Total	Rate		Slope	Drainage density	Hypsometric index	3-hour rainfall	Slope	Drainage density	Hypsometric index	3-hour rainfall	Total	For maximum 1 square mile with 100 percent burn 1st year[3]	For year of observed flood and actual area burned[3]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)
	La Crescenta Area:	*Square miles*		*Square miles*			*Cubic yards*	*Cubic yards per square mile*	*Cubic yards per square mile*	*Feet per mile*	*Miles per square mile*		*Inches*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Cubic yards*	*Cubic yards*
1	Dunsmuir	0.84	1933	0.78	1938	5	58,800	70,000	695,000	1,390	1.7	0.54	2.94	99	97	98	67	64	1,220,000	106,000
2	Eagle-Goss	.61	1933	.46	1938	5	40,900	67,050	767,000	1,480	3.3	.25	2.89	100	84	33	64	18	342,000	19,400
3	Haines	1.53	1933	1.01	1938	5	52,000	33,990	423,000	1,040	2.4	.46	2.85	92	95	98	62	52	1,010,000	117,000
4	Hall-Beckley	.83	1933	.63	1938	5	86,300	103,980	1,185,000	930	2.2	.50	2.82	88	96	100	61	59	990,000	73,000
5	Hay	.20	1933	.06	1938	5	12,600	63,000	1,190,000	1,290	.6	.65	2.72	97	99	76	56	40	760,000	9,700
6	Pickens	1.84	1933	1.75	1938	5	122,200	66,410	650,000	940	3.4	.47	2.93	88	82	99	67	48	910,000	160,000
7	Shields	.27	1933	.24	1938	5	33,500	124,000	1,320,000	1,570	2.5	.51	2.90	100	94	100	65	61	1,160,000	34,400
8	Snover	.23	1933	.11	1938	5	16,800	73,040	1,110,000	1,280	3.5	.54	2.82	97	81	98	61	46	874,000	15,500
	Pasadena Area:																			
9	Fair Oaks	.21	1935	.21	1938	3	12,000	57,140	257,000	1,180	0	.21	2.34	95	100	25	36	9	171,000	9,600
10	Fern	.30	1935	.30	1938	3	20,700	69,000	310,000	1,180	4.8	.41	2.42	95	51	92	39	17	323,000	24,600
11	Las Flores	.45	1935	.31	1938	3	36,000	80,000	495,000	1,610	3.2	.58	2.62	100	85	94	49	39	741,000	60,000
12	Lincoln	.50	1935	.50	1938	3	8,000	16,000	72,000	780	4.6	.31	2.39	81	57	60	38	11	209,000	25,600
13	West Ravine	.25	1935	.24	1938	3	29,800	119,200	555,000	1,290	0	.40	2.40	97	100	90	38	33	627,000	39,500
14	Bailey	.58	1953	.46	1954	1	65,000	112,070	140,000	1,520	2.6	.50	1.70	100	93	100	12	11	209,000	104,000
	Burbank Area:																			
15	Brand	1.03	1927	.77	1943	[4]10	3,100	3,010	99,000	910	3.0	.50	1.70	87	88	100	12	9	171,000	5,300
16	Sunset	.44	1927	.42	1938	[4]10	6,600	15,000	495,000	1,610	2.0	.48	1.93	100	97	99	18	17	323,000	4,800
17	Stough	1.65	[4]	[4]	1943	[4]	33,500	20,300	670,000	1,020	4.4	.62	2.64	91	63	85	52	25	475,000	20,000
	Beverley Hills Area:																			
18	Nichols	.94	[4]	[4]	1938	[4]	17,900	19,040	626,000	480	.9	.56	2.48	57	99	96	42	23	437,000	12,600

[1] See fig. 3 for location.
[2] Computed by use of equation 5 (see text) and adjusted for size of drainage area.
[3] 1,900,000 times total percent from column 19.
[4] 10 years or more assumed to have no effect on debris production.

FIGURE 12

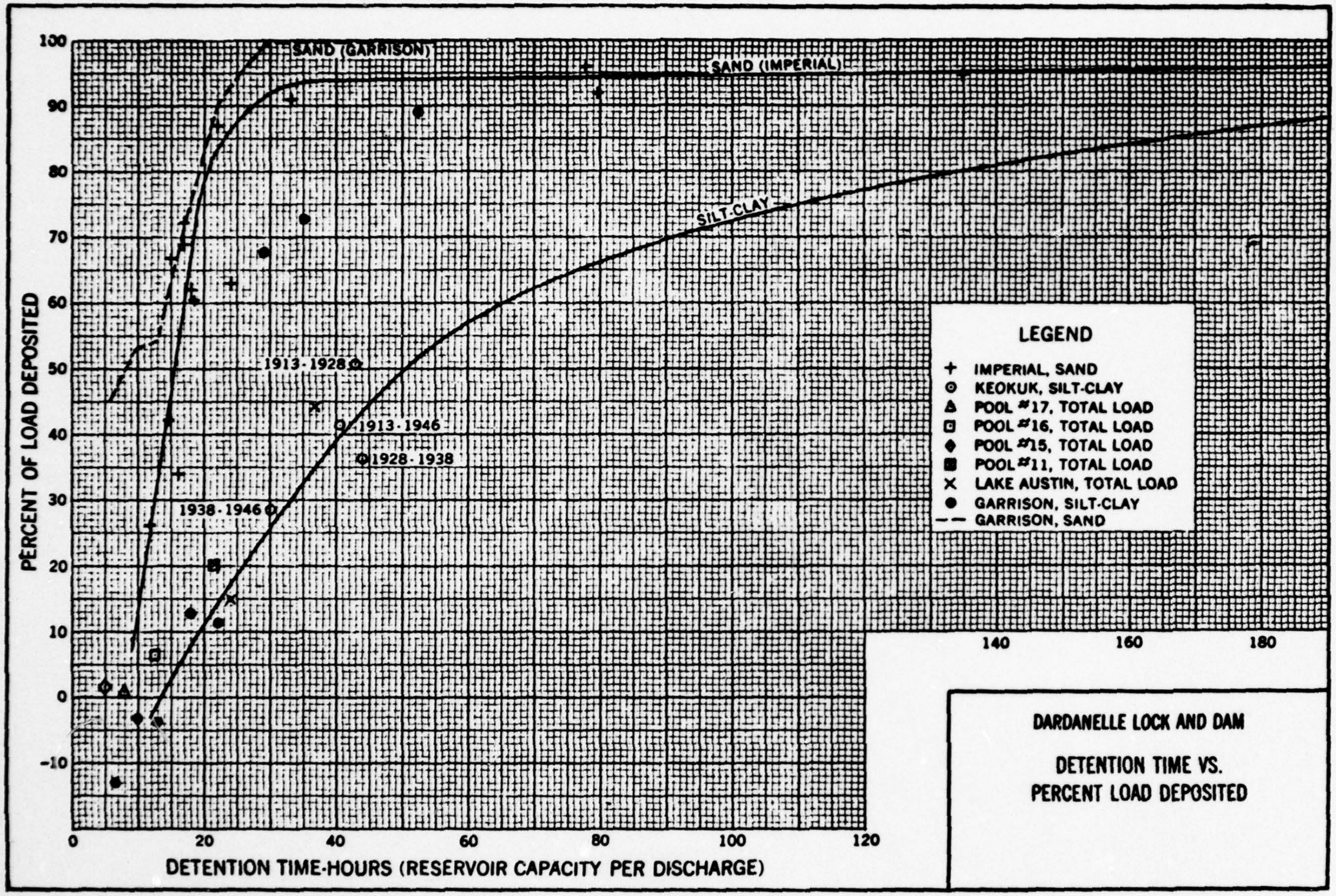

DARDANELLE LOCK AND DAM
DETENTION TIME VS.
PERCENT LOAD DEPOSITED
LEGEND
IMPERIAL, SAND
KEOKUK, SILT-CLAY
POOL #17, TOTAL LOAD
POOL #16, TOTAL LOAD
POOL #15, TOTAL LOAD
POOL #11, TOTAL LOAD
LAKE AUSTIN, TOTAL LOAD
GARRISON, SILT-CLAY
GARRISON, SAND
SAND (GARRISON)
SAND (IMPERIAL)
SILT-CLAY
1913-1928
1913-1946
1928-1938
1938-1946
PERCENT OF LOAD DEPOSITED
DETENTION TIME-HOURS (RESERVOIR CAPACITY PER DISCHARGE)

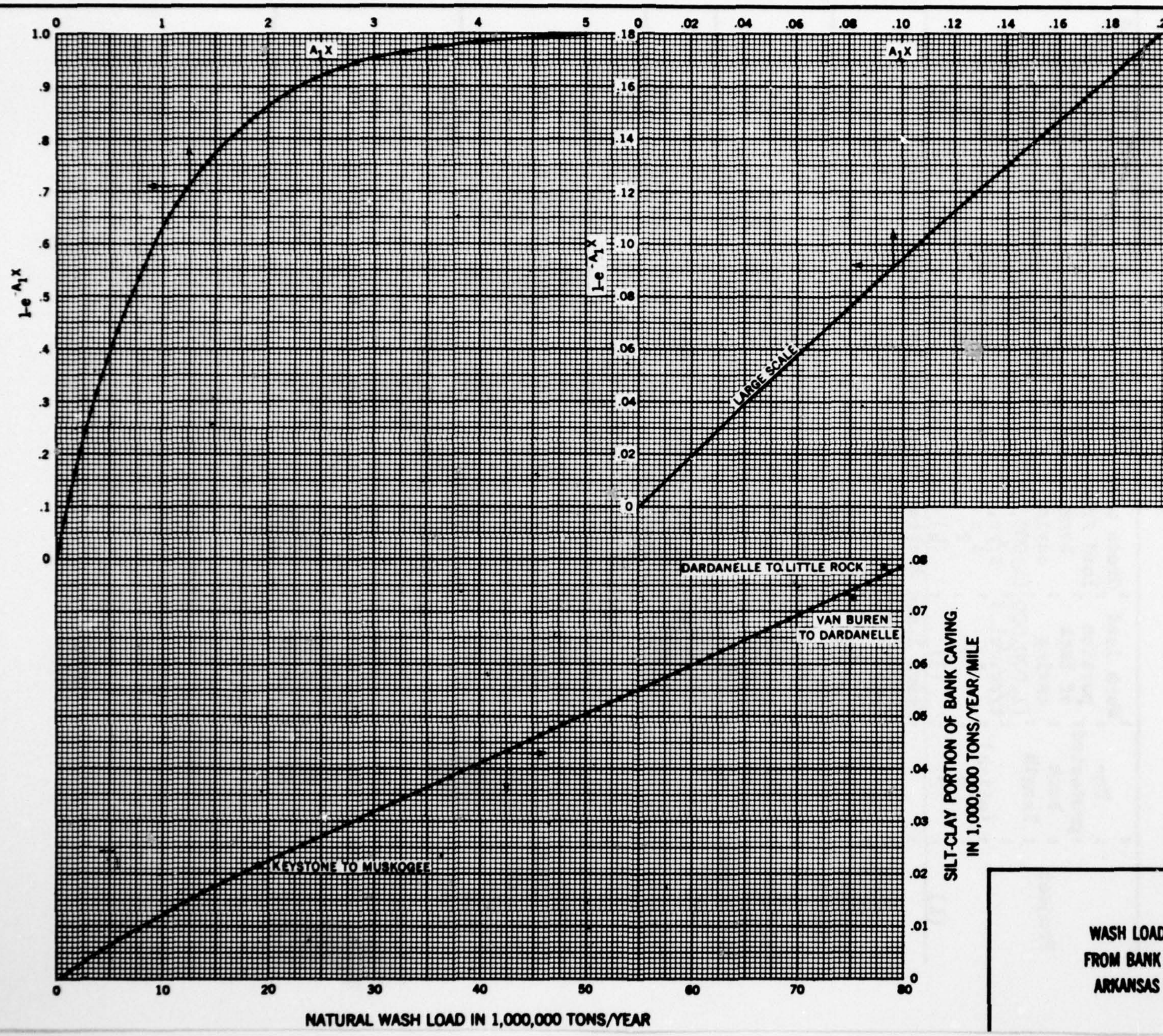
FIGURE 13

FIGURES 14 and 15 OMITTED

WASH LOAD FROM BANK CAVING

Project	Unprotected bank length (miles) x	Wash load portion of bank caving (1,000,000 t/yr./mi.) A_2	Gross wash load from bank caving (1,000,000 t/yr.) A_2x	Natural wash load at projects (1,000,000 t/yr.) A_2/A_1	$A_1x = \frac{A_2x}{A_2/A_1}$	$1-e^{-A_1x}$	Net wash load at lower end of reach from bank caving (1,000,000 t/yr.) L
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		Years 1 and 2 after closure of Dardanelle					
		(Keystone to Verdigris River)					
Keystone	79	.0209	1.65	18.1	.091	.087	1.57
Total			1.65				1.57
		(Verdigris River to Webbers Falls)					
Keystone	112	.0209	2.34	18.1	.129	.121	2.19
Oologah	60	.0036	.22	2.8	.079	.075	.21
Ft. Gibson	41	.0105	.43	8.5	.051	.049	.42
Total			2.99				2.82
		(Eufaula to Arkansas River)					
Eufaula	27	.0375	1.01	36.2	.028	.027	.98
Total			1.01				.98
		(Webbers Falls to Van Buren.)					
Keystone	144	.0209	3.01	18.1	.166	.153	2.77
Oologah	92	.0036	.33	2.8	.118	.111	.31
Ft. Gibson	73	.0105	.77	8.5	.091	.087	.74
Tenkiller	45	.0010	.04	.7	.057	.055	.04
Eufaula	59	.0375	2.21	36.2	.061	.059	2.14
Wister	61	.0007	.04	.5	.080	.076	.04
Total			6.40				6.04
		(Van Buren. to Dardanelle)					
Keystone	171	.0209	3.57	18.1	.197	.179	3.24
Oologah	119	.0036	.43	2.8	.154	.142	.40
Ft. Gibson	100	.0105	1.05	8.5	.123	.116	.99
Tenkiller	72	.0010	.07	.7	.100	.095	.07
Eufaula	86	.0375	3.22	36.2	.089	.085	3.08
Wister	88	.0007	.06	.5	.120	.113	.06
			8.40				7.84

FIGURE 16



WASH LOAD DATA
FROM BANK CAVING
ARKANSAS RIVER

FIGURE 1

APPENDIX 4

PROCEDURE FOR DEVELOPING A TRAP EFFICIENCY CURVE

NOTE: This information was presented in Project Design Memorandum No. 6, Sedimentation-Part IV, Section II. Deposition in Dardanelle Reservoir, Arkansas River and Tributaries, Multiple-Purpose Plan, Arkansas and Oklahoma, U.S. Army Engineer District, Little Rock, Corps of Engineers, Little Rock, Arkansas, October 1957.

TABLE 12

SEDIMENT DATA FOR KEOKUK (POOL NO. 19)

Date of range survey	Storage capacity acre-feet	Years between surveys	Lost capacity Acre-feet	Lost capacity Acre-feet per year	Dry weight Lb/cu.ft.
June 1913	479,600				
Average	425,000	15	109,300	7,300	50
June 1928	370,300				
Average	353,000	10	33,300	3,300	52
June 1938	337,000				
Average	325,000	8	25,000	3,100	54
June 1946	312,000				
Total		33	167,600		

Date	Deposits t/yr Total	Deposits t/yr Silt-clay	Sediment Inflow t/yr Total	Sediment Inflow t/yr Silt-clay	% Deposited silt-clay	Average flow (c.f.s.)	Flow, 10% time (c.f.s.)	Detention time (hours)
1913-28	7,940,000	7,146,000	15,560,000	14,000,000	51.0	58,700	118,000	43
1928-38	4,200,000	3,780,000	11,515,000	10,400,000	36.4	48,000	97,000	44
1938-46	4,450,000	4,005,000	15,430,000	13,900,000	28.8	65,000	131,000	30
1913-46	5,950,000	5,355,000	14,300,000	12,900,000	41.6	57,000	118,000	40.5
Computed deposits from silt-clay curve on Plate 22.								
1913-28		6,601,000						
1928-38		4,939,000						
1938-46		4,518,000						
1913-46		5,705,000						

and sediment range resurveys were made in 1928, 1938, and 1946. By 1946, after 33 years of operation, the reservoir had lost 167,600 acre-feet, or 35 percent of its capacity. The results of these surveys are shown in "Reservoir Sedimentation Data Summary" and in Table 12 herein with the average inflow for the periods between surveys.

40. In 1956 the Rock Island District spudded at eight locations spaced throughout the reservoir and obtained unit weights and grain size distribution of the deposits. From those data an average dry weight of 55 pounds per cubic foot was computed. The deposits in a reservoir become denser with age. Using the terminal unit weight of 55 pounds per cubic foot and the formula listed below by Lane and Koelzer (2) as a guide, unit dry weights of 50 to 54 pounds were assumed for the periods as shown in Table 12. The formula is:

Weight of sand = 93 pounds/cu. ft.

Weight of silt = 65 + 5.7 log (No. of years of deposit)

Weight of clay = 30 + 16 log (No. of years of deposit)

The size distribution of the deposits used were 10 percent sand, 53 percent silt, and 37 percent clay. The volumes of deposits were then converted to weight in tons as shown in Table 12. Conversion of the deposits to weight was necessary to compare with the sediment load inflow which was of course sampled in terms of percent of sediment by weight of water mixture.

41. The next step was to estimate the sediment inflow to Keokuk for the different periods. The flow-duration curves were determined for the periods as shown on plate 20. The Rock Island District has sampled the

suspended load at Burlington, Iowa, near the head of the Keokuk pool during the years 1944 to 1950 and determined the average annual suspended load. The Soil Conservation Service has also made similar estimates. An average load curve is shown on Plate 21 which is intended to include both suspended and bed load. By applying the flow-duration curves on Plate 20 to the average load curve on Plate 21, the average annual inflowing load for each period between range surveys was computed. As the load curve on Plate 21 is based on sediment measurements after construction of the upstream pools Nos. 11 to 17, it was necessary to correct the loads for the periods 1913-28, 1928-38, and 1938-46 to allow for the sediment which was trapped in those pools (deposits in those pools are described in par. 43). Finally, the silt-clay loads for the respective periods were separated from the total load as shown in Table 12. Grain-size analysis of samples by the Rock Island District indicate that the load is composed of about 10 percent sand and 90 percent silt-clay. The primary interest in Keokuk herein is the silt-clay fraction. The percentages of inflowing silt-clay load deposited in the reservoir for the four periods are shown in Table 12.

42. In order to develop a relationship between detention time and percent of sediment deposited for the respective periods between resurveys it is necessary to know the representative detention time to plot since it varies with each discharge. It was found that the best trial-plotting position was for a discharge corresponding to the percent of time when about half the load was transported, or 10 percent of the time for Keokuk. The detention times for flows occurring 10 percent of the time are shown in Table 12. The plotted points of detention time versus percent of

TABLE 13

SEDIMENT DEPOSITS - KEOKUK (POOL NO. 19)
1913-1928

Increment of time %	Inflow 1,000 c.f.s.	Silt-clay load 1,000 t/day (1)	Days/yr.	Silt-clay wtd. by time t/day	Detention time hours (2)	% Silt-clay deposits (3)	Silt-clay deposit 1,000 t/day (4)
2.5	13.7	1.4	9.12	40	375	98	39
5.0	17.7	2.5	18.25	125	291	96	120
5.0	20.8	3.4	18.25	171	247	94	161
5.0	23.0	4.2	18.25	211	224	92	194
5.0	25.4	5.1	18.25	257	202	90	231
5.0	27.8	6.0	18.25	302	185	87	263
5.0	30.5	7.3	18.25	365	169	85	310
5.0	33.0	8.6	18.25	428	156	83	355
5.0	36.0	10.1	18.25	507	143	81	411
5.0	39.2	12.0	18.25	599	131	79	473
5.0	43.1	14.6	18.25	730	119	77	562
5.0	47.5	17.7	18.25	884	108	75	663
5.0	50.3	19.8	18.25	992	102	73	724
5.0	59.6	27.5	18.25	1,374	86	68	934
5.0	67.5	35.0	18.25	1,750	76	65	1,138
5.0	76.9	45.6	18.25	2,280	67	61	1,391
5.0	87.5	58.7	18.25	2,936	59	57	1,674
~~5.0~~	~~100.5~~	77.5	18.25	3,876	51	51	1,977
5.0	118.0	106.0	18.25	5,301	44	44	2,332
3.75	143.4	156.3	13.69	5,857	36	34	1,991
2.5	168.0	213.0	9.13	5,330	31	27	1,439
1.25	210.0	331.0	4.56	4,133	24	17	703
Tons/day				38,356			18,085
1,000 tons/yr.				14,000			6,601
				From range surveys, Tab. 12			7,146

(1) Without upstream pools.

(2) $\frac{12.1 \times \text{av. capacity}}{\text{Flow}} = \frac{425,000}{\text{Flow}}$

(3) From silt-clay curve of detention times vs. percent deposited, Plate ~~21.~~ 22

(4) Column 7 x column 5.

the silt-clay load deposited are shown on Plate 22 with a curve drawn approximately through the points. An example of the trial computations to check the curve is shown in Table 13 for the 1913-28 period. The percent of time and corresponding discharges, sediment load, and detention times are listed in the table. The detention time is the ratio of the average available level storage for the period divided by the discharges as noted by footnote. The corresponding percentages of sediment deposited are obtained from the silt-clay curve on Plate 22 and multiplied by the loads to obtain the deposits. The sum of these deposits is 6,601,000 tons per year compared to the estimated value of 7,146,000 tons from the range survey, or a discrepancy of about 8 percent for the 1913-28 period. Similarly, the other three periods were tested and the computed deposits are shown in the lower part of Table 12. They may be compared with the silt-clay deposits from the range surveys shown immediately above. It will be noted that the silt-clay curve on Plate 22 is poorly defined for detention times greater than about 50 hours. However, that part of the curve corresponds to the smaller discharges and therefore the smaller sediment loads, so that this part of the curve is relatively insensitive to error.

50. Garrison Reservoir. Garrison is a large multiple-purpose project on the middle Missouri River. On 7-9 July 1954 the suspended load was sampled and the hydraulic elements were measured at a number of ranges starting at the head of backwater and terminating in the lake where most of the load had been deposited. The discharge at the time was about 30,000 cubic feet per second. The results of this survey are

given in reference (29). Similar surveys were made at Fort Peck and Fort Randall. The differences in the concentration at successive ranges indicate the sediment load deposited. The percent deposited upstream from any range may be computed from the data as well as the storages and detention times.

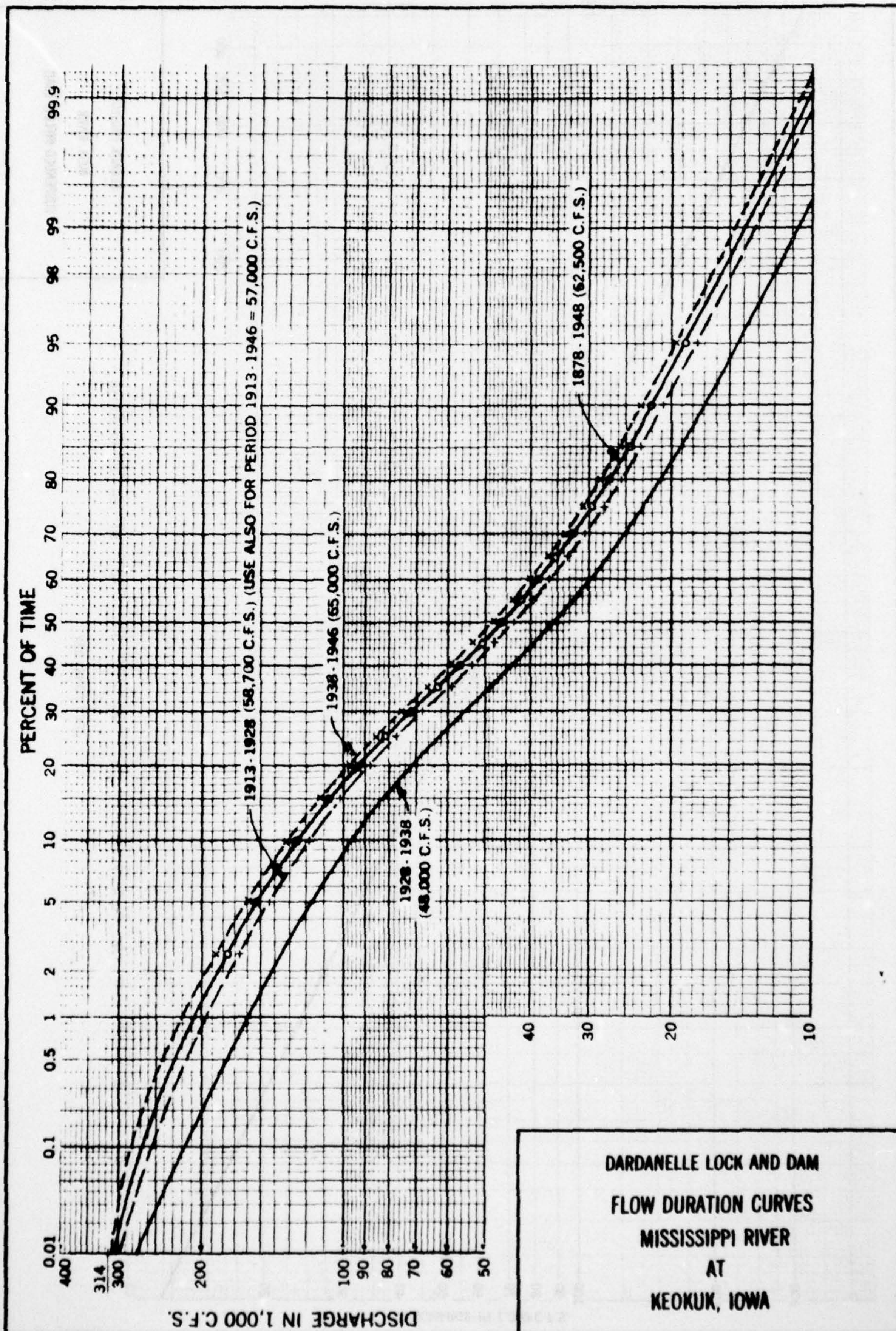
51. A summary of this information for Garrison Reservoir is shown in Table 17. The percent deposits of sand and silt-clay are shown separately. The detention times versus percent of deposits for these two size fractions are shown on Plate 22, representing accumulated values above the respective ranges. The plot of the sand fraction follows the trend of the data shown for Imperial Dam. The silt-clay fraction checks the silt-clay curve shown for short detention times, but indicates a generally steeper curve as will be noted from the points for detention times of 29 to 52 hours. The plotted values showing minus deposits, or scour, may be the result of error in measuring the concentration, although scour will sometimes occur with short detention times. The data are not fully comparable to the other information shown. Storages under the backwater curve were included in computing the detention time and the cross sections used omitted dead water areas. Also, Garrison is a large storage reservoir and the velocities decrease rapidly as the flow reaches the deeper part of the lake. This may account in part for the steep trend of the plotted points, or the more rapid fall out of the suspended load. The data for Fort Peck and Fort Randall indicate a similar trend and are not shown. While this type of information is limited, it is of considerable interest and contributes to the available

records. Further reference is made to the report on these projects in connection with another method considered herein for estimated sediment deposits in Dardanelle Reservoir.

TABLE 17

SEDIMENT DATA FOR GARRISON RESERVOIR, MISSOURI RIVER

Range	Mile and distance	Accumulated storage acre-feet	Discharge c.f.s.	Detention time hours	Suspended sediment concentration: Sand: Concentration p.p.m.	Sand: Accumulated deposits p.p.m.	Sand: Percent deposited	Silt-clay: Concentration p.p.m.	Silt-clay: Accumulated deposits p.p.m.	Silt-clay: Percent deposited
Sanish Bridge	1,558		29,800		392			1,085		
	13	16,000		6.5		176	45		-137	-13
22	1,545		29,800		216			1,222		
	7	24,500		10		208	53		-35	-3
23	1,538		29,800		164			1,120		
	6	31,800		13		212	54		-47	-4
23A	1,532		29,800		180			1,132		
	9	44,500		18		289	74		143	13
23D	1,523		29,800		103			942		
	6	53,600		22		354	90		121	11
23E	1,517		29,800		38			964		
	6	70,500		29		389.6	99.5		741	68
24	1,511		29,800		2.4			344		
	4	87,200		35		390.4	99.6		796	73
25	1,507		29,800		1.6			289		
	8	127,200		52		391.4	99.8		963	89
26	1,499				0.6			[illegible]		

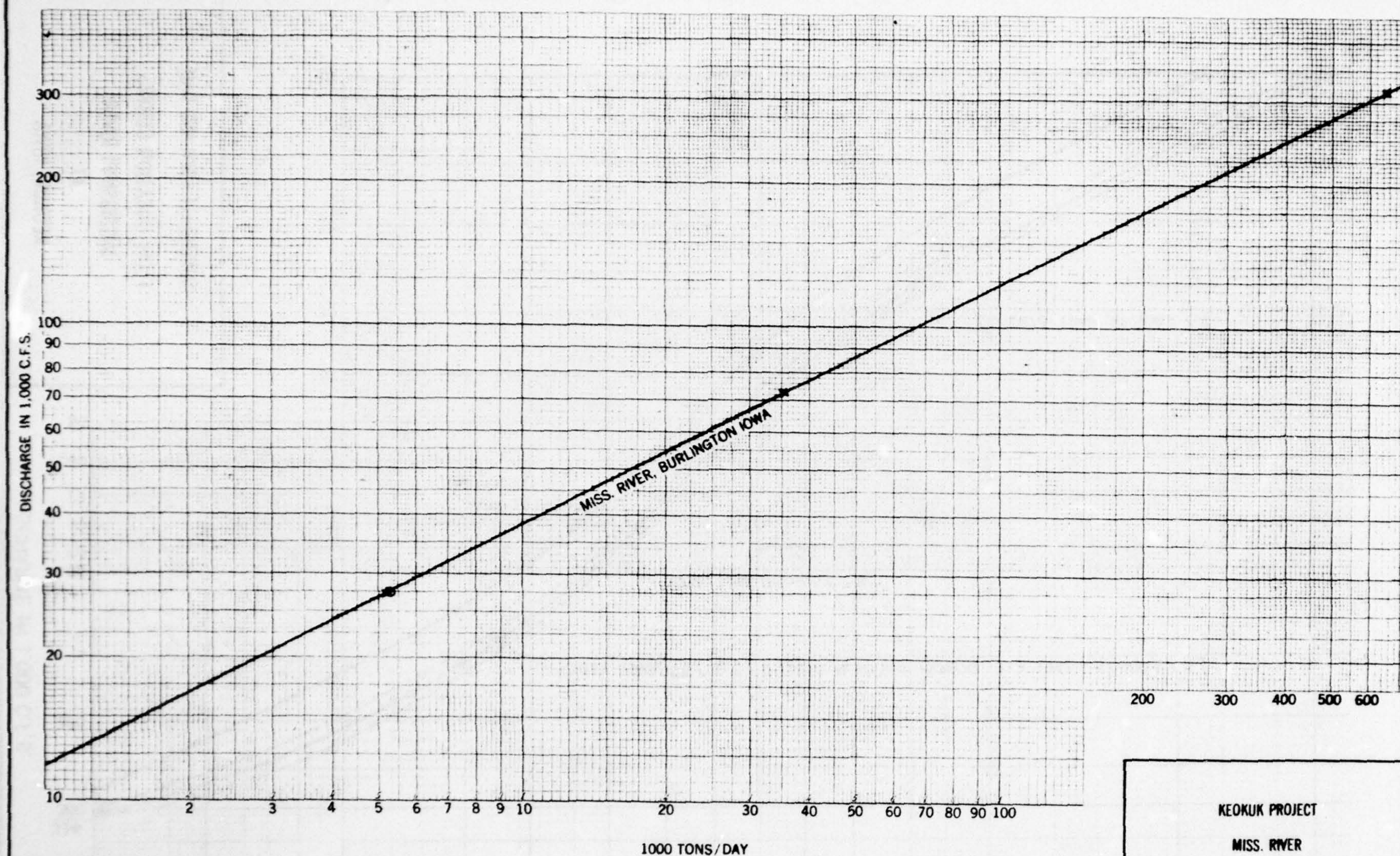


DARDANELLE LOCK AND DAM

FLOW DURATION CURVES
MISSISSIPPI RIVER
AT
KEOKUK, IOWA

CORPS OF ENGINEERS

U. S. ARMY

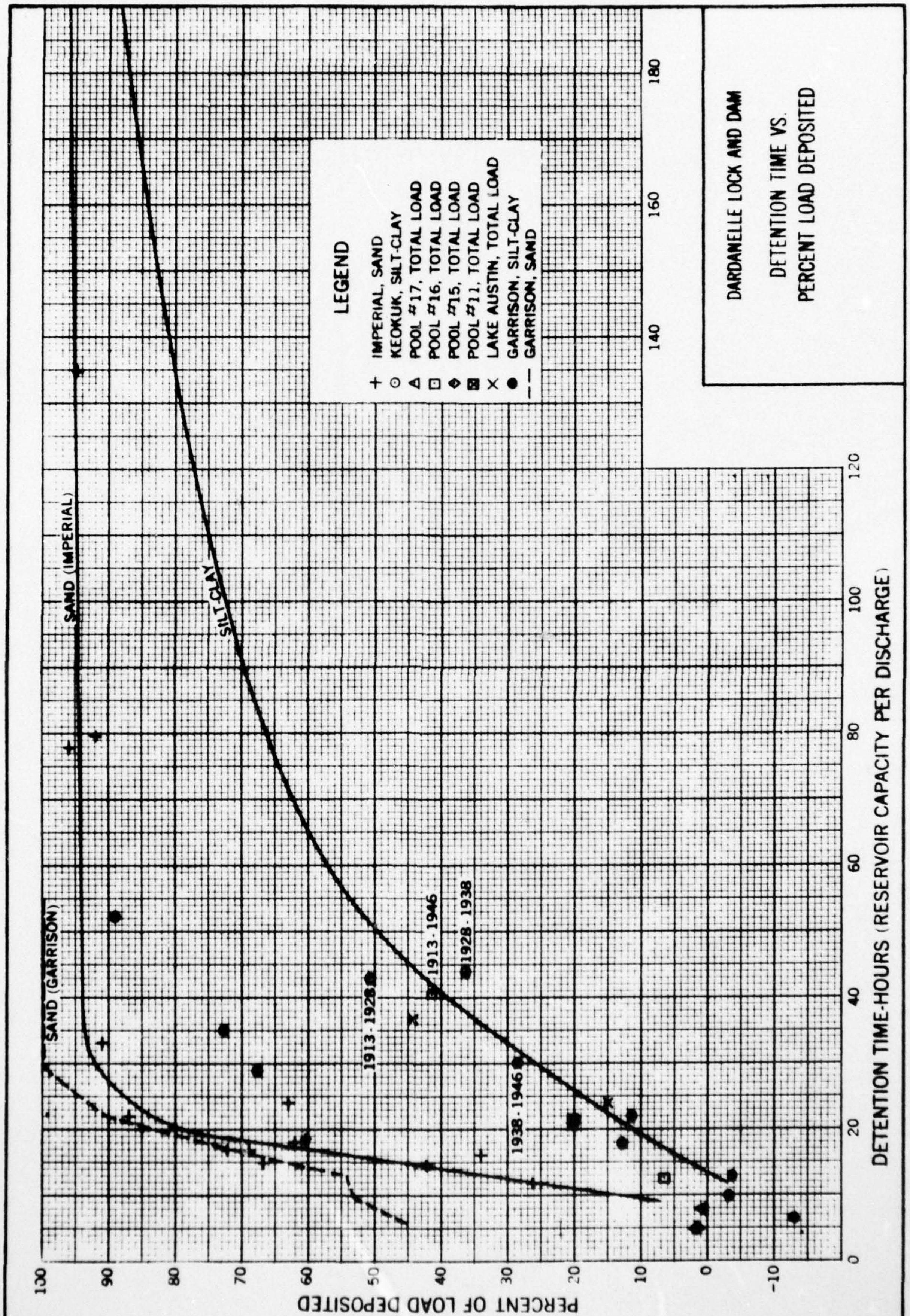


KEOKUK PROJECT

MISS. RIVER

SUSPENDED INFLOW LOAD

PLATE 21


DARDANELLE LOCK AND DAM
DETENTION TIME VS. PERCENT LOAD DEPOSITED
LEGEND
IMPERIAL, SAND
KEOKUK, SILT-CLAY
POOL #17, TOTAL LOAD
POOL #16, TOTAL LOAD
POOL #15, TOTAL LOAD
POOL #11, TOTAL LOAD
LAKE AUSTIN, TOTAL LOAD
GARRISON, SILT-CLAY
GARRISON, SAND
SAND (IMPERIAL)
SAND (GARRISON)
SILT-CLAY
1913-1928
1913-1946
1928-1938
1938-1946
PERCENT OF LOAD DEPOSITED
DETENTION TIME-HOURS (RESERVOIR CAPACITY PER DISCHARGE)
100
90
80
70
60
50
40
30
20
10
0
-10
0
20
40
60
80
100
120
140
160
180

APPENDIX 5

FORECASTING DISTRIBUTION OF SEDIMENT DEPOSITS IN LARGE RESERVOIRS

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HYDROLOGIC ENGINEERING METHODS FOR WATER RESOURCES DEVELOPMENT.--ETC(U)
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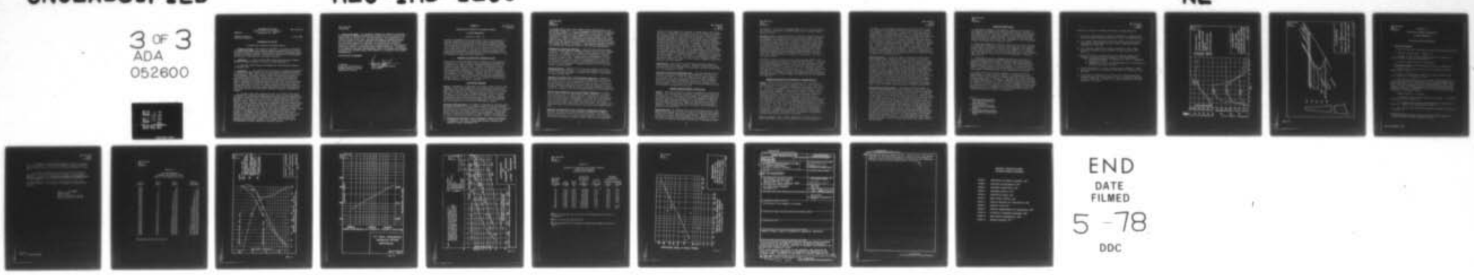

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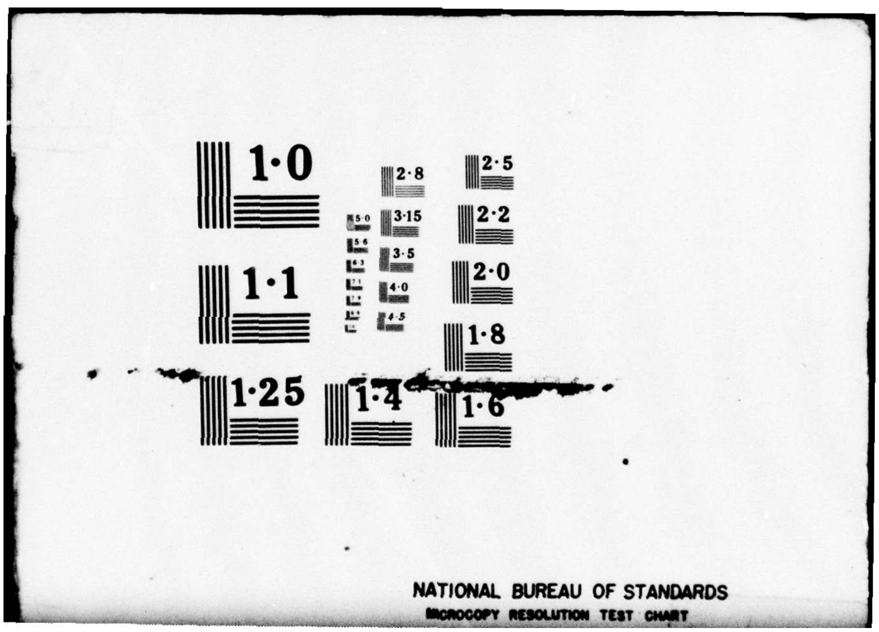
1·0
2·8
2·5
3·15
2·2
3·5
2·0
4·0
1·1
4·5
1·8
1·25
1·4
1·6
NATIONAL BUREAU OF STANDARDS
MICROCOPY RESOLUTION TEST CHART

DEPARTMENT OF THE ARMY
Office of the Chief of Engineers
Washington, D.C. 20315

ETL 1110-2-64

ENGCW-EY

Engineer Technical
Letter No. 1110-2-64

7 July 1969

ENGINEERING AND DESIGN

Distribution of Reservoir Sediment Deposits

1. Purpose and Scope. The purpose of this ETL is to present a discussion of problems associated with reservoir sediment accumulations and to review pertinent planning and design considerations relating to anticipated distributions of reservoir deposits. This letter is applicable to all Divisions and Districts concerned with civil works activities.

2. References: a. Paper entitled "Forecasting Distribution of Sediment Deposits in Large Reservoirs," by Brice L. Hobbs (Appendix I).

b. EM 1110-2-4000, "Reservoir Sedimentation Investigations Program," 15 November 1961.

3. Discussion: a. The importance of forecasting the probable distribution of reservoir sediment deposits is often overlooked in planning and design investigations. Many recent project design reports present only one or two brief paragraphs concerning the gross volume of storage space depletion anticipated during the period considered for economic investigation and make no reference to possible serious problems that might be created by adverse distributions of sediment deposits in particular areas or elevation zones. Conditions at certain reservoirs which have been in operation for long periods point up the need for making sediment distribution studies in connection with most reservoir design investigations; this is particularly true of all projects on streams which transport substantial quantities of sediment.

b. In most of the check computations made in the Office of the Chief of Engineers in reviewing the methodology and results of field measurements, the results obtained by the "Pool-Elevation Duration Method," presented with Appendix I, have been found to give results comparing favorably with the measured values. However, there are a few instances where the values estimated for certain elevation zones depart appreciably from the measured values reported in the "Reservoir Sediment Data Summaries" submitted in accordance with EM 1110-2-4000 (ref 2b). This is also true of estimates obtained by other methods. The reasons for some of these discrepancies are obscure while in others, examination of the records yield logical explanations. For example, it is doubtful that conditions of deposition in Jemez Canyon Reservoir in New Mexico could have been accurately predicted by any of the currently available empirical methods, since substantial quantities of material have accumulated in reservoir-elevation zones high above the maximum experienced pool elevation, and it appears likely that some of the deposition is wholly unrelated to reservoir effects.

4. Action to be Taken. The information presented in Appendix I discusses various types of upstream sedimentation problems that may be induced by the construction and operation of a dam and reservoir. The computational procedures outlined in the report, and those described in references therein, are representative of methods available for estimating the locations of future sediment deposits in reservoirs. The practices and techniques described in Appendix I have been found by long experience to give generally satisfactory results in estimating future sediment conditions. Accordingly, it is suggested that Corps representatives utilize the methods and techniques outlined in the inclosed report, where feasible, in connection with sediment investigations.

FOR THE CHIEF OF ENGINEERS:

I Appendix
Forecasting Distribution of
Sediment Deposits in Large
Reservoirs, 10 Feb 69

WENDELL E. JOHNSON
Chief, Engineering Division
Civil Works

APPENDIX I

FORECASTING DISTRIBUTION OF SEDIMENT DEPOSITS IN LARGE RESERVOIRS

by Brice L. Hobbs 1/

Reservoir impoundments disrupt the natural order of the processes of sediment transportation in streams and the results range from those that are relatively insignificant to those where undesirable deposition is expected to seriously affect the utility of the project within a relatively short period of time. It is the purpose of this discussion to characterize some of the problems, discuss certain practical considerations regarding the importance of forecast estimates and to present some approaches for approximating future distributions of sediment deposits in large artificial reservoirs.

RESERVOIR CLASSIFICATION ACCORDING TO SIZE

Usually there is a considerable degree of ambiguity in designation of a reservoir as "large" or "small". The capacities of the reservoirs considered herein range from about 60,000 to 20,000,000 acre-feet at elevations of the spillway crests. Perhaps the descriptive terms "large" or "small" should not be emphasized in discussions of reservoir sedimentation; comparisons of relationships such as capacity-inflow ratios are more meaningful. However, the size of a reservoir (and therefore, the areal changes associated with pool fluctuations) is one of the more important influences affecting the distribution of sediment deposits. Accordingly, the vague demarcation between large and small reservoirs is likely to persist.

DISTRIBUTION PROBLEMS

General - Information on sedimentation contained in many reservoir planning and design reports suggest that those responsible attach little importance to the possible affects of adverse distribution of the sediment. Often times the only information presented consists of a brief statement to the effect that estimated depletion for 50 or 100 years will represent only a small fraction of the gross storage. In this connection it should be mentioned that there have been some important problems associated with local deposits where depletion of gross storage is not expected to be serious for 1000 years or longer.

Depletion of Storage Space - If volumetric reductions of reservoir storage space allocated for various purposes represented the only problems associated with reservoir sedimentation, forecast information of fractional distributions of total deposits would not serve any particularly useful purpose even where rapid gross depletion is anticipated. If such were the case it would only be necessary to make appropriate reallocations as would be indicated by periodic resurveys. However, the significance

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of storage depletion and other related problems depend generally upon the average sedimentation rates and progressive distribution of deposits. On alluvial streams, it is usually important to have forecast estimates of the probable distributions of deposits both with respect to areal location and volumetric accumulations in various elevation zones. Such information is useful in connection with planning and design considerations to assure that serious encroachments upon space allocated for purposes other than sediment retention will not occur during the period used for economic analysis of the project. Some important sediment distribution problems are discussed further in the following subparagraphs.

Aggradation of Tributary Channels - A reservoir on an alluvial stream is one of the more important manmade influences which may affect channel conditions. The aggradation of channels which sometimes occurs above reservoirs is an extension of the reservoir sedimentation processes which may adversely affect drainage conditions and aggravate flooding problems on adjacent lands. Relatively small fractions of the total accumulations are usually involved in the aggradation of channels in the reaches of reservoir-backwater influences above established pool levels and future dimensions of aggraded channels cannot be accurately forecast by known methods.

Aesthetic Effects - Regardless of the need for sediment distribution estimates for other purposes, it is occasionally important to foresee future conditions which might be unsightly and therefore objectionable to people residing nearby.

Depletion of Storage Space in Single-Purpose Reservoirs - Normally a reasonable estimate of the total volume of sediment anticipated during the period used for economic considerations is all that is necessary for establishing storage requirements in single-purpose reservoirs, and advance information regarding the locations of the deposits is usually not needed. Exceptions may be found in cases where substantial inactive storage is required in reservoirs operated primarily for power production.

Depletion of Storage Space in Multiple-Purpose Reservoirs - In cases where sediment yields are appreciable, advance information of probable future distributions of sediment deposits is important in connection with planning and design considerations of storage depletion regardless of the project purposes. Misjudgments involved in the initial allocations of storage space cannot always be satisfactorily rectified by reallocations of space remaining at some future date. For example, head limitations might preclude lowering the elevation of the minimum power pool.

Depletion of Space Where Water is Stored for Recreational Purposes
Recently, there has been a rapid increase in demands for storage of water for recreational activities in artificial lakes. The needs are usually satisfied by: use of water stored primarily for other purposes; provisions for perpetual storage of a given volume of water regardless

of pool elevation; specific allocations of storage below a given pool elevation; or arrangement for regulation so as to provide for a minimum pool having storage not exceeding that provided for conservation and the undepleted space initially reserved for sediment. There is general agreement regarding the importance of recreational needs, therefore, the problems that may be expected to result from unfavorable sediment distributions should be recognized. For example, a plan to continuously provide a small pool of fixed volume in the lowest elevation zone of remaining space may become completely unsatisfactory for the planned activity relatively early in the life of the project. Also, decisions are often made, after completion of the design stage and without benefit of additional engineering study, to regulate a reservoir so as to utilize space reserved for sediment deposits for recreational or other conservation purposes. In such cases there is no opportunity for changing the total storage, therefore, the effects of the change on sediment distribution expected to result from the change in regulation procedures should be carefully examined.

Shore Erosion - Shore erosion and bank caving processes frequently create beach and boat harbor problems. Movement of material by these processes may cause an exchange of storage space between elevation-zones or a net storage loss or both.

Utilization of Delta and Backswamp Areas - Interests opposing the construction of reservoirs frequently cite sedimentation as one of the horrible consequences of these developments and the general public is led to believe that the results are always entirely bad. Actually, the program for wildlife propogation, by the U. S. Fish and Wildlife Service, in the delta areas of Denison Reservoir is reported to be quite successful. This represents a type of planning problem that has not had proper consideration in the past.

FACTORS AFFECTING DEPOSIT ACCUMULATIONS

General - The factors involved in reservoir sedimentation processes are numerous. The influences most frequently mentioned in qualitative discussions[1/] are: (1) Reservoir size and shape; (2) Sediment quantities and characteristics; (3) Sediment sources; (4) Progressive vegetative growth on frequently exposed deposits; (5) Consolidation of deposits; (6) Magnitudes, frequency and sequences of hydrologic events; and (7) Reservoir regulation practices. These factors and other influences comingle in ever changing combinations to produce the distribution of deposits at any given time.

Dominant Factors - As indicated above, the distribution as well as the quantities of sediment involved, are sensitive to numerous factor combinations which include unpredictable sequences of flood events and pool elevations coincident with high sediment inflows. Regulation is one of the dominant influences affecting deposition in reservoirs. In fact, the first five factors listed above are governed in some degree by pool

fluctuations. The charts and diagrams shown on Incls 1 and 2 illustrate the effects of regulation on sediment deposition in a large multiple-purpose reservoir.

Incl. No. 1 shows estimated sand loads delivered by a design flood which was developed for a large reservoir on an alluvial stream. The flood was assumed to have started at a time when the pool level was at the bottom of the flood control pool. Attention is directed to the cumulative sand curve which shows that 97 percent of the sand transported by the flood would be delivered to the reservoir before the maximum pool elevation was reached. The sand load graph is based upon an average rating curve and therefore, has the same shape and peak time as the discharge hydrograph; actually maximum suspended sediment concentrations quite often precede peak discharge rates and under such conditions, the cumulative sand curve would be in a position to the left of that shown on Incl 1.

Coincidental values of inflow and pool elevations from graphs on Incl 1 were used to develop the general illustration shown on Incl 2. The locus of the upstream limits of backwater effects in this hypothetical situation further demonstrates why most of the sediment delivered to a large flood-control reservoir, by any given flood, is transported to areas below the higher pool elevations attained. Also, it affords some insight to tendencies for material previously deposited to be redistributed. Reference Nos. 1/ through 5/ contain considerable additional information regarding the manner in which sediment is transported into and deposited in a reservoir.

METHODS FOR ESTIMATING DISTRIBUTION OF SEDIMENT DEPOSITS

General - There are several methods described in the literature for estimating future distributions of sediment deposits. For purposes of this discussion, it is considered satisfactory to classify these methods as: (1) analytical methods[2/, 3/, 4/] which utilize procedures based upon theoretical concepts of hydraulics and sediment transport and (2) purely empirical methods[5/]. All methods are subject to limitations imposed by necessary simplifications involving uncertain assumptions regarding sequences of significant hydrologic events and lack of accountability for other dominant influences which help to produce individual deposition patterns. For example, large tributaries occasionally transport 5 to 10 times the average annual sediment load in a 10-day period and the range of extremes in "low-order" tributaries is often much greater. There is no way of predicting when during the project life, extreme events may occur. The uncertainties and difficulties notwithstanding it is important to make the best possible distribution determination commensurate with probable seriousness of anticipated problems and practical considerations of the purpose of the estimate, available data and time allowed for the study.

Choice of Methods - Where sediment deposition is expected to have a major effect upon the design and operation of a reservoir project, it

is prudent to use more than one approach so that the results of somewhat independent determinations can be used as guidance for judgment in allowances for conservatism. In many project investigations it is impracticable to attempt detailed analyses, to consider the probable effects of many individual influences, because of insufficient data and a number of other limitations. With present knowledge, the writer believes that in most cases the results obtained by empirical methods are sufficiently reliable for engineering purposes. However, there are many cases where thoroughly rigorous sedimentation analyses are imperative. Dardanelle Reservoir[4/] is one example. Also, there are cases where serious tributary channel and flood-plain aggradation may be expected to accompany delta developments. In some of these situations, it may be found reasonable to use empirical methods to establish the initial condition assumed for the starting point in an analytical study of patterns of continued deposition.

Empirical Methods - In practice, empirical methods are being used in most instances where sediment distribution estimates are required. These methods have the advantage of simplicity but sacrifice consideration of some important influences and when followed implicitly, these methods often produce misleading results. This is true of the method presented herewith as well as all of those described in literature known to the writer. All depend upon the same basic requirements for estimates of total sediment loads, average trap efficiencies and gross volumes of sediment trapped during the period under consideration. None delineate developments at individual tributaries. The methods described by Borland and Miller[5/] are probably most widely used in the United States; it is believed that the principal weakness of these methods is that no particular consideration is given to the sediment characteristics or the operational effects of the reservoirs. The method presented in Incl 3 also has obvious weaknesses but consideration is given to sediment characteristics and regulatory influences.

. Pool-Elevation Duration Method - This empirical method attempts to account for the influences of reservoir regulation inherent in a pool-elevation duration curve, general effects of the fraction of sand materials involved and the size and shape of the reservoir. The approach is based upon the idea that pool elevation and the size characteristics of the sediment are two of the most important factors influencing deposition in given elevation zones. It also embodies the thesis that: (1) over a long period of time, sediment delivered by medium and moderate floods will establish some statistical order of coincidence with pool elevations between the maximum and minimum and (2) that regulation of the rare floods (and therefore, the distribution of sediment deposited in the higher elevation zones) will be similar. This suggests that there may be some reasonably definable relationships between duration of a given pool and the amount of sediment that will be deposited above and below the elevation of that pool. Step procedures for one simple approach are presented in Incl 3. This index method is based upon limited data and its reliability for general application will require much more testing. There are several refinements that appear worthy of further study.

CONCLUDING OBSERVATIONS

1. The Reservoir Sediment Data Summaries assembled and published by the Committee on Sedimentation, Water Resources Council, represent the most complete source of available information on sediment distribution but relatively few of these data summaries contain information regarding the sediment size characteristics. Also, many of the formal sediment survey reports, which present these summaries and other information, contain little useful data on particle sizes.

2. Some thought might well be given to the utility of certain information presented in accordance with the instructions issued for preparing certain items of the Reservoir Sediment Data Summaries. For example, in some large reservoirs the capacity at the elevation of the spillway crest elevation may bear little or no relationship to the trap-efficiency; some other capacity value would often be more meaningful in capacity-inflow ratios.

3. A great mass of reservoir sediment data has been collected on a routine basis according to somewhat arbitrary observation schedules. Analytical studies of these data to establish useful relationships for general application and to identify data collection deficiencies have lagged far behind the data collection programs. It is believed that some of the money being used for surveys should be diverted for funding some intensive analytical studies of the information now available.

4. Without the aid of electronic computers, it would generally be impracticable to attempt rigorous analytical investigations aimed at predicting future distributions of sediment deposits in large reservoirs having a large number of tributaries. Important advances have been made in computer applications in hydrologic analyses relating to flood inflows and regulation of reservoirs. Also, considerable progress has been made in the use of electronic computers in sediment discharge determinations.[6/] The possibilities for integrating these techniques appears to offer the greatest promise for development of improved analytical procedures for investigating reservoir sediment distributions.

Incls
1. Illustration-Coincidental Sand Inflows & Reservoir Pool Elevations
2. Illustration-Locus of Upstream Limits of Reservoir Effects
3. Paper-"Forecasting Sediment Distribution in Large Reservoirs"

References on subject of Sediment Distribution in Large Reservoirs

1/ E. W. Lane, "Some Aspects of Reservoir Sedimentation," India Central Board of Irrigation and Power Journal, V. 10, No. 2-3 (Apr-July 1953).

2/ L. C. Fowler, "Determination of Location and Rate of Growth of Delta Formations," Missouri River Division, Corps of Engineers, Sediment Memoranda No. 6, Nov 1957.

3/ A. S. Harrison, "Deposition at Heads of Reservoirs," Proc. Fifth Hydraulics Conference, State University of Iowa, June 9-11, 1952; Bul. 34.

4/ Project reports for "Arkansas River and Tributaries, Arkansas and Oklahoma," prepared by Corps of Engineers, Little Rock District

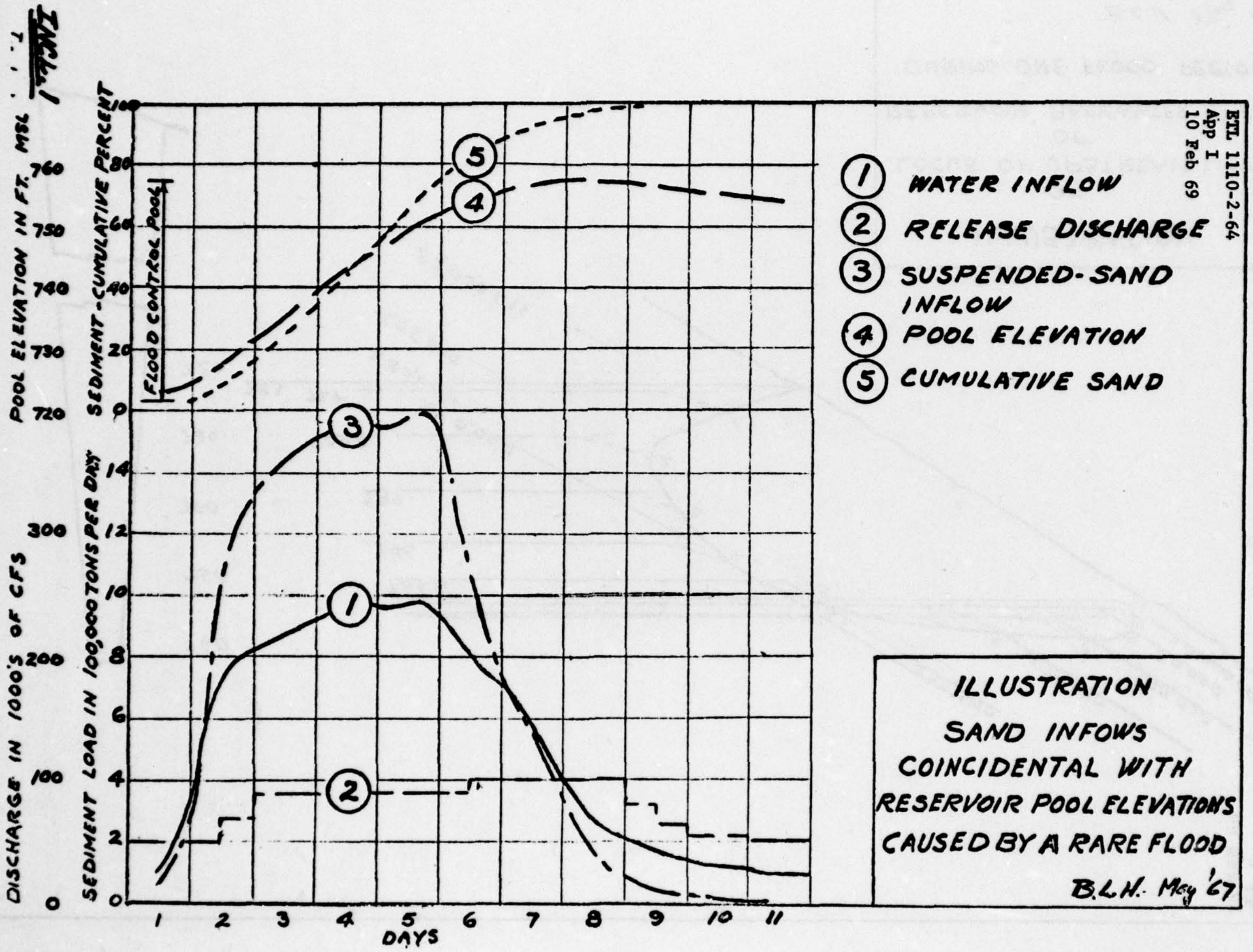
(a) "Design Memorandum No. 6, Sedimentation - Part IV, Dardanelle Reservoir," Oct 1957.

(b) "Supplement to Project Design Memorandum No. 6-4, Sedimentation, Dardanelle Reservoir, Jan 1959.

5/ W. M. Borland and C. R. Miller, "Distributions of Sediment in Large Reservoirs," Am. Soc. Civil Engrs. Journ, Hyd, Div., Vol 86, p. 61-87, Apr 1960.

6/ "A Procedure for Computation of the Total River Sand Discharge and Detailed Distribution, Bed to Surface", by F. B. Toffaleti, Nov 1968 (Technical Report No. 5, Committee on Channel Stabilization, Corps of Engineers, U. S. Army).

Incl 1


POOL ELEVATION IN FT. MSL
SEDIMENT-CUMULATIVE PERCENT
DISCHARGE IN 1000'S OF CFS
SEDIMENT LOAD IN 100,000 TONS PER DAY
FLOOD CONTROL POOL
DAYS
1 WATER INFLOW
2 RELEASE DISCHARGE
3 SUSPENDED-SAND INFLOW
4 POOL ELEVATION
5 CUMULATIVE SAND
ILLUSTRATION
SAND INFOWS
COINCIDENTAL WITH
RESERVOIR POOL ELEVATIONS
CAUSED BY A RARE FLOOD
B.L.H. May '67

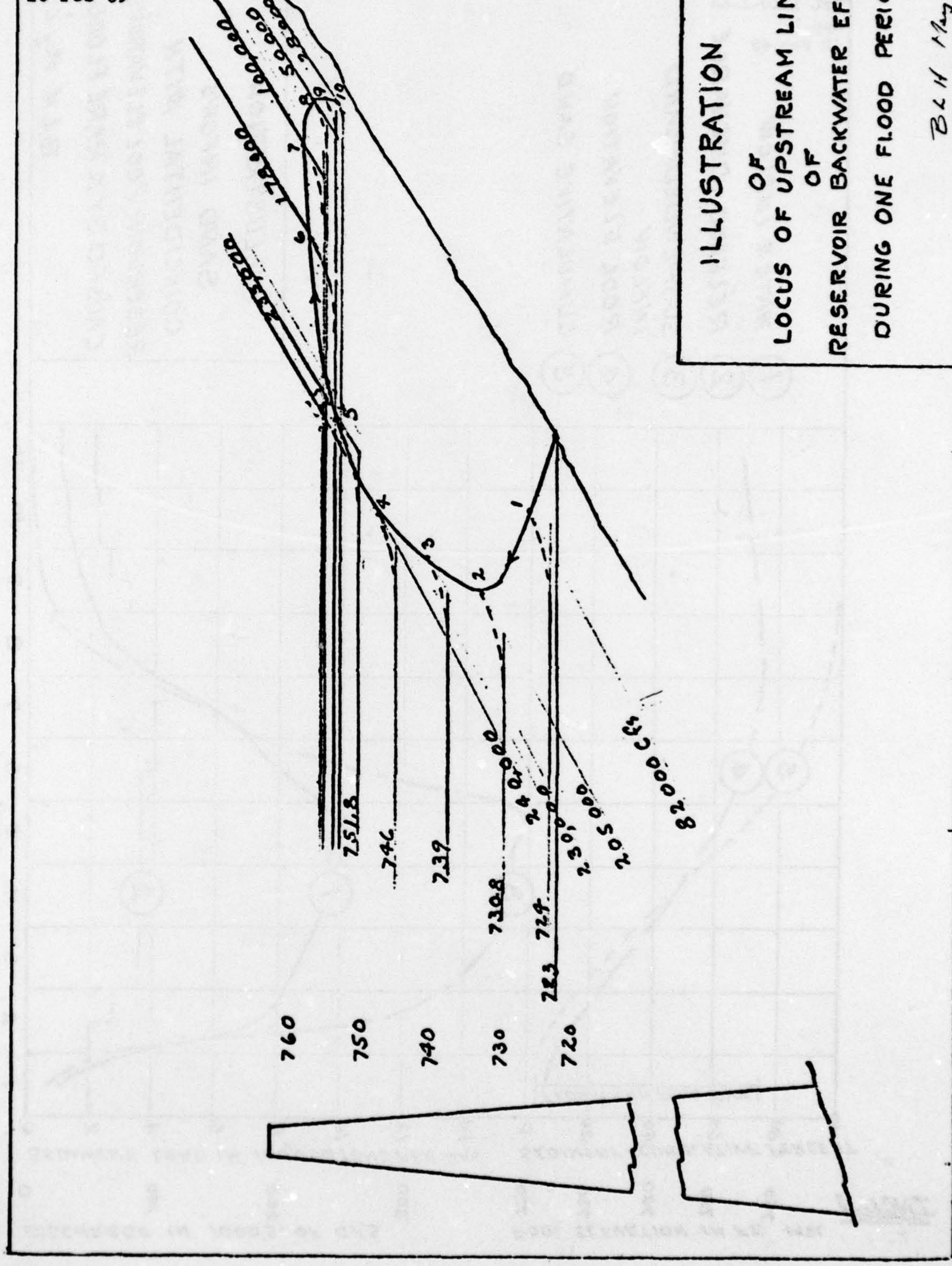


ILLUSTRATION
OF
LOCUS OF UPSTREAM LIMITS
OF
RESERVOIR BACKWATER EFFECTS
DURING ONE FLOOD PERIOD
BLH May 1967
760
750
740
730
720
751.8
746
739
730.8
724
82,000 cfs
205,000
230,000
178,000
100,000
50,000 cfs

Incl 2

INCLOSURE 3 1/

FORECASTING SEDIMENT DISTRIBUTIONS

IN LARGE RESERVOIRS

POOL-ELEVATION DURATION METHOD

1. Required information.

a. Pool elevation charts developed in connection with operation studies.

b. Reservoir capacity table. (Table No. 1)

c. Estimate of total volume of sediment expected to accumulate in reservoir during period under consideration.

d. Estimate of sand fraction of total deposit.

2. Estimating procedure (use Ft. Peck Reservoir data for explanation).

a. Develop the pool elevation duration curve from pool elevation graphs (Curve 1, Fig. 1).

b. Plot first differences of capacity for depth increments (five-foot increments) on log-log paper. (Fig. 2)

c. Draw estimated distribution curve on Fig. 3 with position based on the sand-percent scale (four percent for Ft. Peck) and judgment of the plotting positions of points determined from measurements at other reservoirs. The right envelope position was selected because of the low percentage of sand and the large capacities of pools in the operating range (from about 110,000 to 19,000,000 acre-feet). (Sand scale shown on Fig. 3 is explained in paragraph 3 below.)

d. Prepare Table No. 2 as follows:

(1) Tabulate time durations (10 percent, 20 percent ... 95 percent and 100 percent) in column No. 1.

(2) Tabulate pool elevations corresponding to the durations in column No. 2 (obtain values from Curve No. 1, Fig. 1).

(3) Tabulate first differences of capacity (obtained from Fig. 2) in column No. 4.

1/ Incl 3 with paper "Forecasting Distribution of Sediment Deposits in Large Reservoirs," by Brice L. Hobbs, 10 Feb 69.

(4) Compute ratios (first differences of capacity divided by the first difference of capacity corresponding to the pool elevation that is exceeded only five percent of the time) and tabulate in column No. 5.

(5) Enter the chart (Fig. 3) with ratios from column No. 5 and tabulate the corresponding values of percent of total sediment deposits in column No. 6. These values represent the estimated distribution of deposits. Measured values are tabulated in column No. 7.

3. The sand-percent scale on Fig. 3 is plotted from values taken from Fig. 4 which is a correlation of percentages of sand with total deposits.

Brice L. Hobbs

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Hydrology & Hydraulics Branch
Engineering Division, CW. OCE

Incl. 3 (Sheet 2 of 2)

TABLE NO. 1

FORT PECK RESERVOIR
CONDENSED AREA-CAPACITY TABLE
(Based on 1961 Aggradation Survey)

ELEV (m.s.l.)	DEPTH (Ft.)	AREA (Acres)	CAPACITY (Acre-Feet)
2033	0	0	0
2035	2	103	113
2040	7	402	1,214
2045	12	1,075	5,002
2050	17	1,652	11,109
2055	22	2,305	21,423
2060	27	4,149	36,870
2070	37	10,672	106,662
2080	47	16,714	245,371
2090	57	22,966	440,692
2100	67	29,732	702,113
2110	77	38,458	1,042,665
2120	87	50,560	1,484,307
2130	97	61,391	2,044,261
2140	107	71,243	2,709,084
2150	117	81,944	3,474,396
2160	127	92,712	4,346,056
2170	137	106,393	5,335,418
2180	147	122,028	6,485,415
2190	157	936,912	7,777,395
2200	167	152,792	9,222,634
2210	177	170,021	10,839,099
2220	187	187,829	12,625,547
2230	197	206,874	14,600,015
2240	207	226,827	16,771,900
2250	217	246,919	19,138,489
2260*	227	270,200	21,704,684

*Extrapolated above elevation 2250

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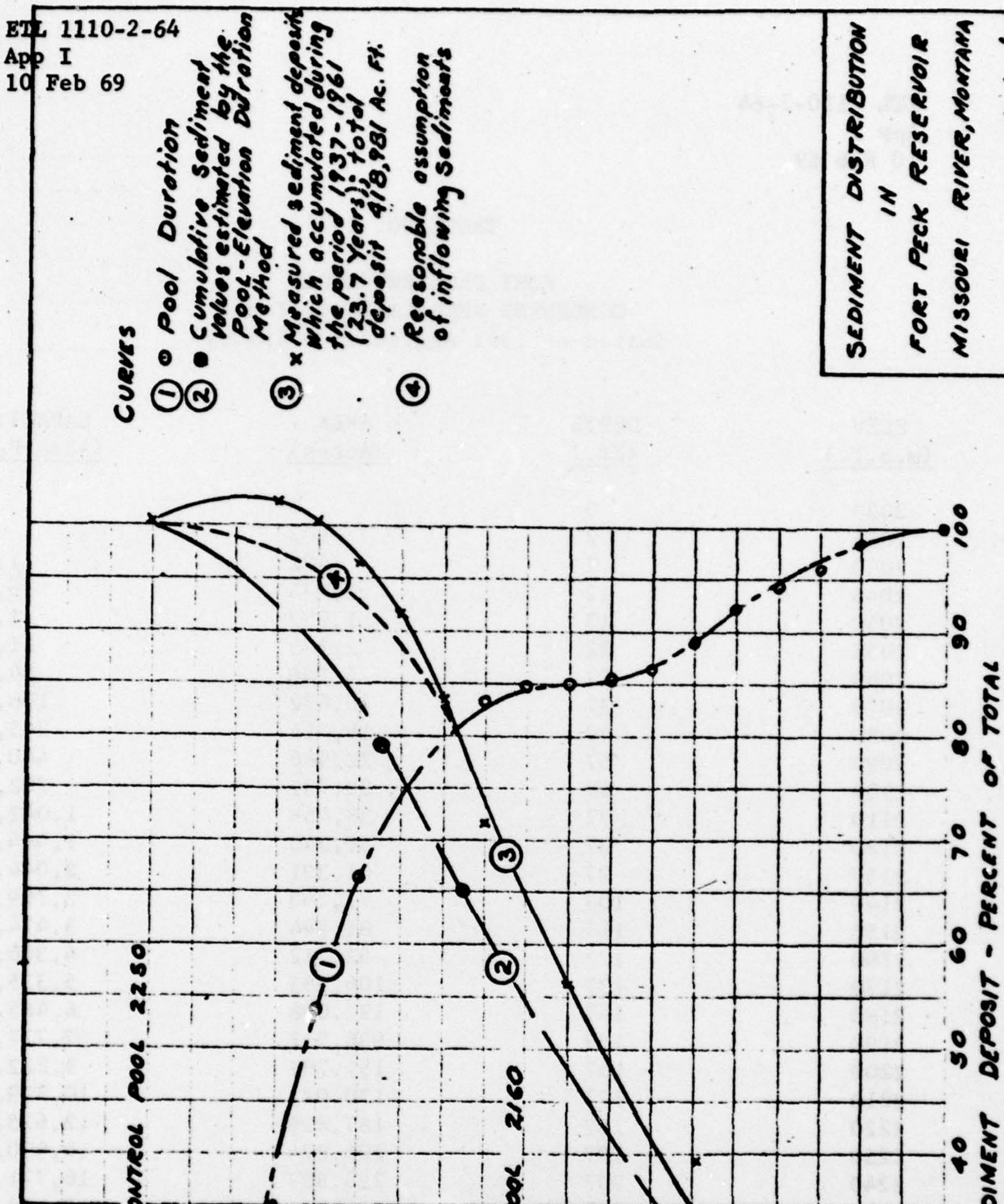
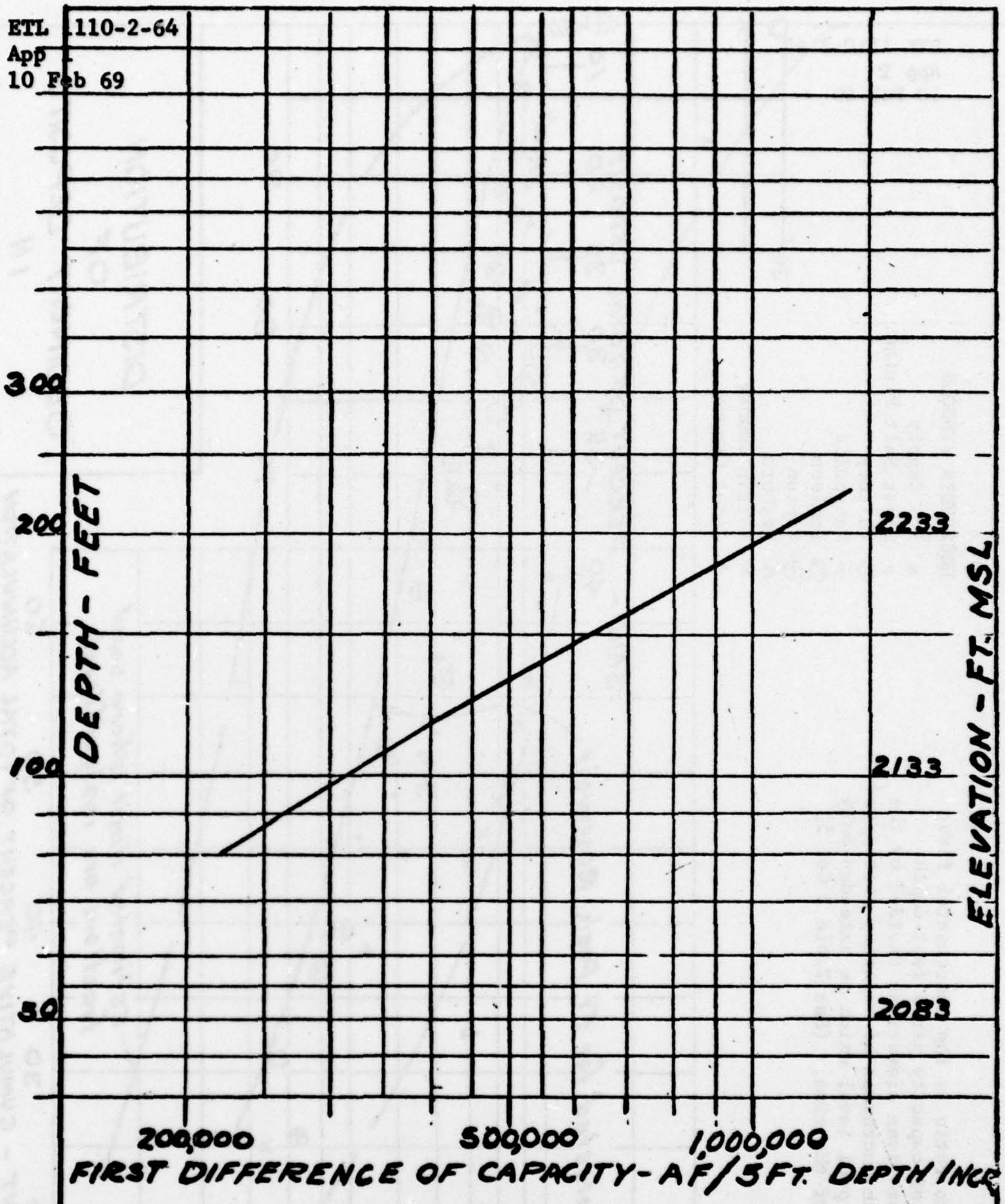


Fig. 1



FT. PECK RESERVOIR
MISSOURI RIVER
MONTANA

BLH May '67

FIG 2

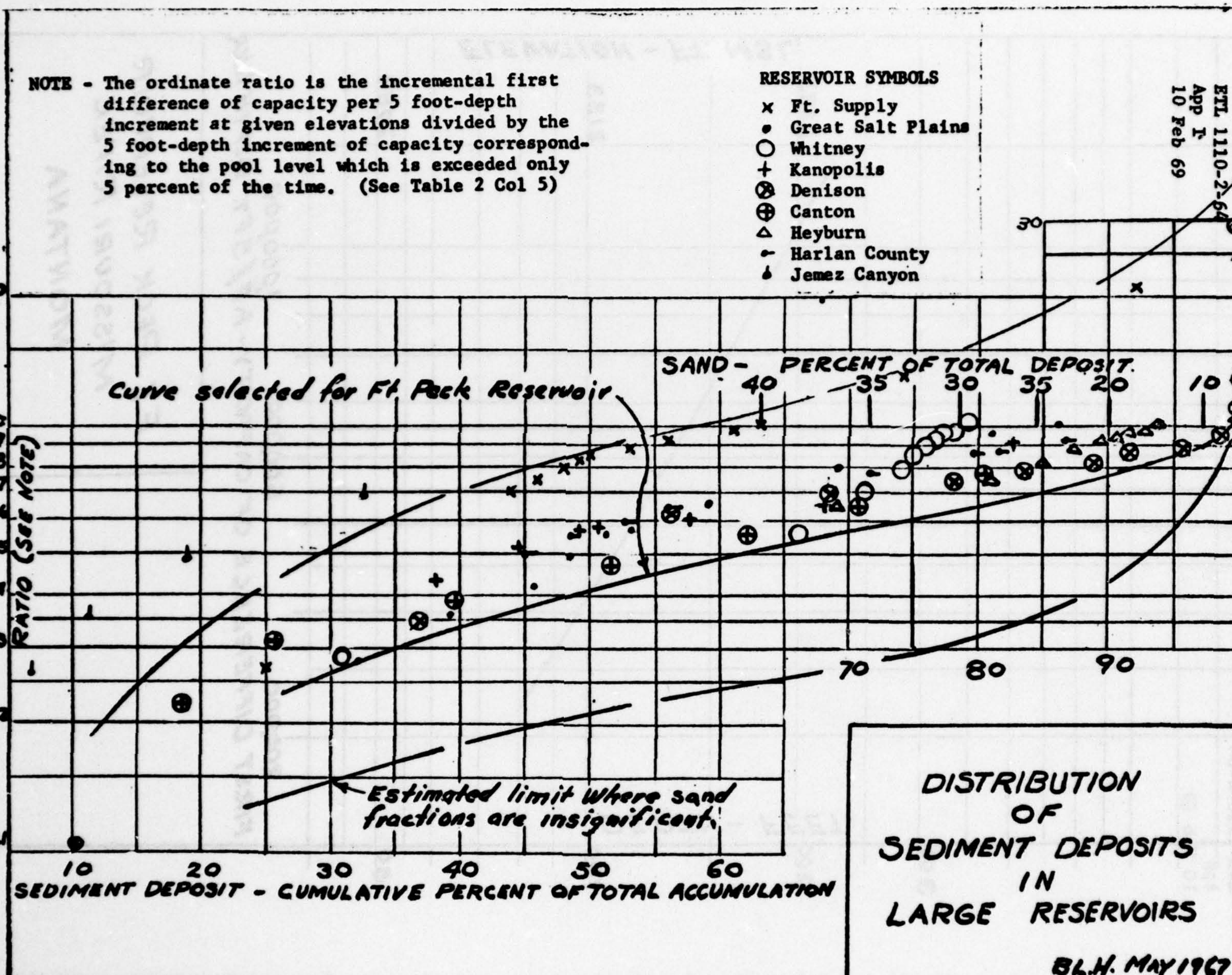

NOTE - The ordinate ratio is the incremental first difference of capacity per 5 foot-depth increment at given elevations divided by the 5 foot-depth increment of capacity corresponding to the pool level which is exceeded only 5 percent of the time. (See Table 2 Col 5)
RESERVOIR SYMBOLS
× Ft. Supply
• Great Salt Plains
○ Whitney
+ Kanopolis
⊗ Denison
⊕ Canton
△ Heyburn
- Harlan County
Jemez Canyon
SAND - PERCENT OF TOTAL DEPOSIT
40
35
30
35
20
10
30
Curve selected for Ft Peck Reservoir
RATIO (SEE NOTE)
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
70
80
90
Estimated limit where sand fractions are insignificant
10
20
30
40
50
60
SEDIMENT DEPOSIT - CUMULATIVE PERCENT OF TOTAL ACCUMULATION
DISTRIBUTION OF SEDIMENT DEPOSITS IN LARGE RESERVOIRS
B.L.H. May 1967

FIG 3

TABLE NO. 2

ESTIMATE OF DISTRIBUTION OF SEDIMENT DEPOSITS
IN FORT PECK RESERVOIR
MISSOURI RIVER, MONTANA

POOL ELEV. DURATION (Percent of Time)[1]	ELEV (Ft MSL)	DEPTH (Ft)	FIRST DIFF OF CAPACITY (Ac-Ft/5-Ft Depth Increment)	RATIO[2] (Col. 4 ÷ 1,125,000)	SEDIMENT DISTRIBUTION ESTIMATED (Σ %)	SEDIMENT DISTRIBUTION MEASURED (Σ %)[3]
(1)	(2)	(3)	(4)	(5)	(6)	(7)
10	2,117	84.0	236,000	0.27	30.0	32.0
20	2,116.5	143.5	580,000	0.52	65.0	78.5
30	2,195	162.0	722,600	0.64	79.0	92.0
40	2,208	175.0	828,000	0.74	88.0	95.5
50	2,212	179.0	862,000	0.77	90.0	97.8
60	2,218	185.0	915,000	0.81	94.0	98.8
70	2,225	192.0	987,000	0.88	97.0	99.5
80	2,230	197.0	1,030,000	0.92	98.5	99.8
90	2,236	203.0	1,090,000	0.97	99+	
95	2,240	207.0	1,125,000	1.00	99.5	99.95
100	2,248	215.0	1,200,000	1.07	100.0	100.0

[1] Percent of time pool was at or below corresponding elevation shown in Column No. 2.

[2] Ratio is 1.0 at the 95 percent pool.

[3] Values from Item No. 26 of Reservoir Sediment Data Summary (See Curve 3 Fig 1).

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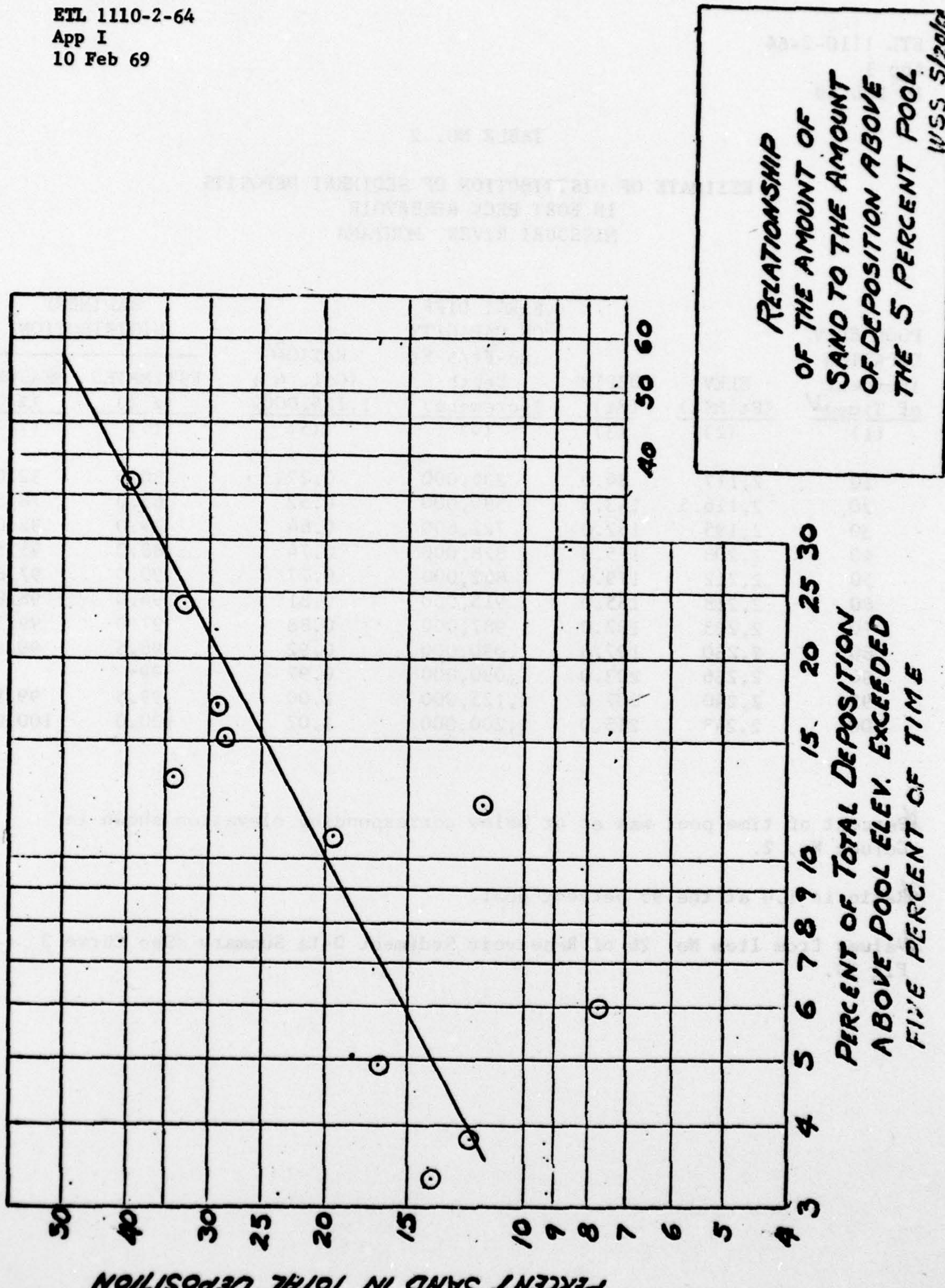

FIG. 4

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This is part of the 12-volume report entitled "Hydrologic Engineering Methods for Water Resources Development," prepared by the Hydrologic Engineering Center (HEC) as part of the U.S. Army Corps of Engineers' participation in the International Hydrological Decade.

This volume addresses the topics of river morphology, data collection and analysis, reservoir sedimentation, and aggradation and degradation in free-flowing streams. The emphasis of the volume is on practical approaches and next page

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cont. techniques for analyzing sediment problems. Application of digital computer simulation for calculating the volume and location of sediment deposits in reservoirs, and for predicting aggradation or degradation trends downstream from dams as well as in free flowing streams, is discussed.

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